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PMR Graphite Engine Duct Development

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1.0 SUMMARY

This report presents the results of the effort performed under Contract NAS3-21854. The objective of this program was to demonstrate the cost and weight advantages that could be obtained by utilizing the graphite/PMR15 material system to replace titanium in selected turbofan engine applications. This was accomplished both by analytical evaluations and by the fabrication and test of critical subcomponents and actual engine hardware.

The initial effort on this program was directed toward the design and evaluation of bypass duct type structures common on military turbofan engines. This type of structure was chosen because it had the potential of utilizing a relatively simple manufacturing approach while still demonstrating the ability to design and fabricate a highly loaded major engine structure out of an advanced composite material which would have cost and weight advantages over current metal designs. The specific component addressed during this part of the program was the outer bypass duct of the GE-F404 engine. This component is a sophisticated metal part made by forming and machining titanium plates which are then extensively chemically milled (chem-milled) to reduce the weight as much as possible.

A composite version of the F404 outer duct was designed utilizing graphite fabric in a PMR15 matrix as the primary structural material. This composite version was designed to meet all the load, stiffness, and functional requirements of the existing titanium duct. With only minor bracket modifications, the composite duct was interchangeable with the titanium duct. In support of this composite design, a material property data base was generated which had the statistical basis necessary to validate the design and analysis. In addition, subcomponent tests were conducted to evaluate such areas as bolted attachments, flanges, and buckling of circular shells.

Based on these data, the design of the composite version of the F404 outer duct was finalized, and two ducts were fabricated. The first complete duct was subjected to a proof pressure test prior to installation on a ground test engine. The test subjected the duct to an internal pressure of one and one-half times the normal operating pressure. No damage was noted, and the duct was then run for over 1900 hours on several ground test engines. No duct-related difficulties were encountered during engine tests. The second duct was assembled in a static test set-up and was loaded to 210% of design limit load with no damage to the duct. The test was terminated at this point due to facility limitations.

At this point in the program, the cost benefit study was completed. The results of this study indicated that the composite version of the duct would be 14% lighter than the titanium duct and, at the 250th unit, a 30% cost savings could be achieved.

Based on the successful utilization of composites on the F404 outer duct, it was decided to investigate the potential advantages of these composite materials in more complex engine components. The fan stator assembly of the F404 engine was selected for this study. In this

study, both the fan case and the stator vanes were considered for the potential application of advanced composite materials. After an extensive study, it was concluded that it would be feasible to fabricate both the first-stage stator vanes and the fan stator case using advanced composite materials. However, due to the many constraints imposed by trying to replace an existing metal structure with a composite structure, the cost of the composite version of the F404 fan stator assembly was not competitive with the cost of the existing metal structure. It was apparent from this study that if composites are to be effectively used in complex engine hardware, the parts must be initially designed for composite application rather than attempting to make a composite version of an existing metal part.

This program has demonstrated that it is feasible to design and fabricate major engine hardware using advanced composite materials. On relatively simple structures, such as an outer bypass duct, significant cost and weight savings can be obtained through the direct substitution of composites for existing metal structures. For more complex hardware, with more interface requirements, it is necessary for the parts to be initially designed with composites in mind in order to achieve the potential cost and weight advantages available through the use of these materials.

2.0 INTRODUCTION

During the past 15 years, the basic feasibility of fabricating major engine structure utilizing advanced composite materials has been demonstrated through the fabrication and test of a number of components. However, most of these components have been located in the cooler portions of the engine because of the temperature limitation of graphite/epoxy which received most of the initial attention, due to its availability and advanced stage of development. The use of advanced composites in the higher temperature regions has been paced by the slower emergence of the polyimide-type matrix systems.

The first series of polyimides to be investigated were of the condensation cure type and were difficult to process; subsequently, additional reaction-type systems were developed, which were some improvement, but still presented difficult processing problems. One of the first polyimide-type matrix systems to offer relative ease of processing combined with good, consistent part quality at a competitive cost was PMR15, developed by the NASA-Lewis Research Center.

The potential of this system was first explored during the NASA-sponsored QCSEE (quiet, clean, short-haul experimental engine) Program. As part of that program, the graphite/PMR system was developed to the point where sufficient data was available to design and build a composite core cowl (Figure 1) for the QCSEE.

The successful performance of the QCSEE core cowl during engine operation led to a study of the potential benefits of this material system in the design of a more highly loaded, production-oriented, engine component. The part selected for this study was the outer duct of the GE-F404 engine which powers the Navy's F-18 strike fighter (Figure 2). This duct was then a sophisticated titanium part (Figure 3) made by forming and machining titanium plates, which were then extensively chemically milled to reduce the duct weight. GEAE then completed a preliminary design of a composite version of this duct that could substitute directly for the metal duct. This composite version was designed to perform all of the functions, carry all engine and flight loads, and tolerate all engine environmental conditions that the metal duct had to sustain. The basic concept of this design consisted of a solid laminate shell with titanium end flanges which were riveted to the ends of the shell. The projected cost and weight benefits of this composite design were of sufficient magnitude to warrant further development.

Based on results of the above study, NASA and the Navy jointly funded the program described in this report.

Figure 1. Core Cowl Doors.

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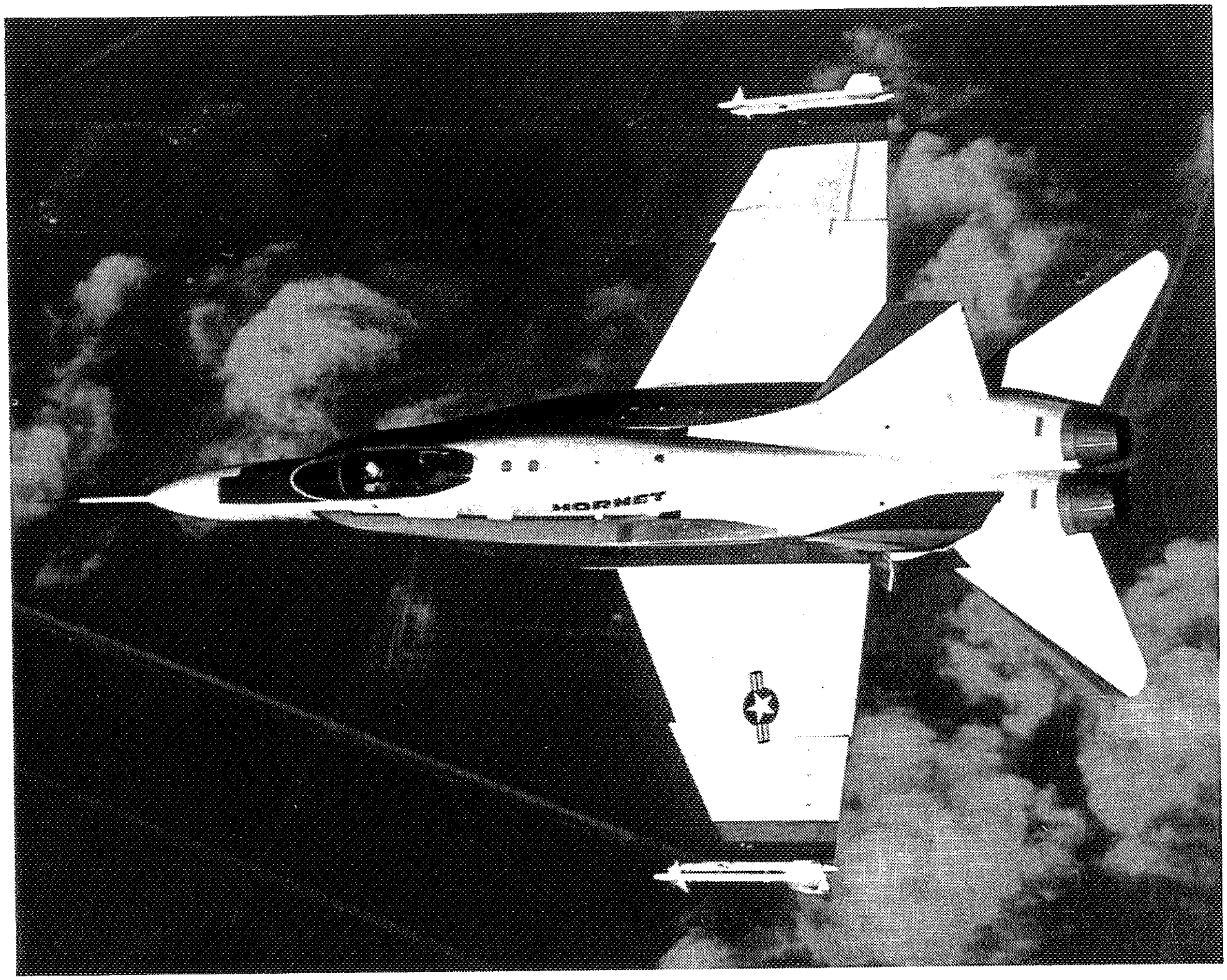

Figure 2. Navy F-18 Strike Fighter Powered by the GE-F404 Engine.

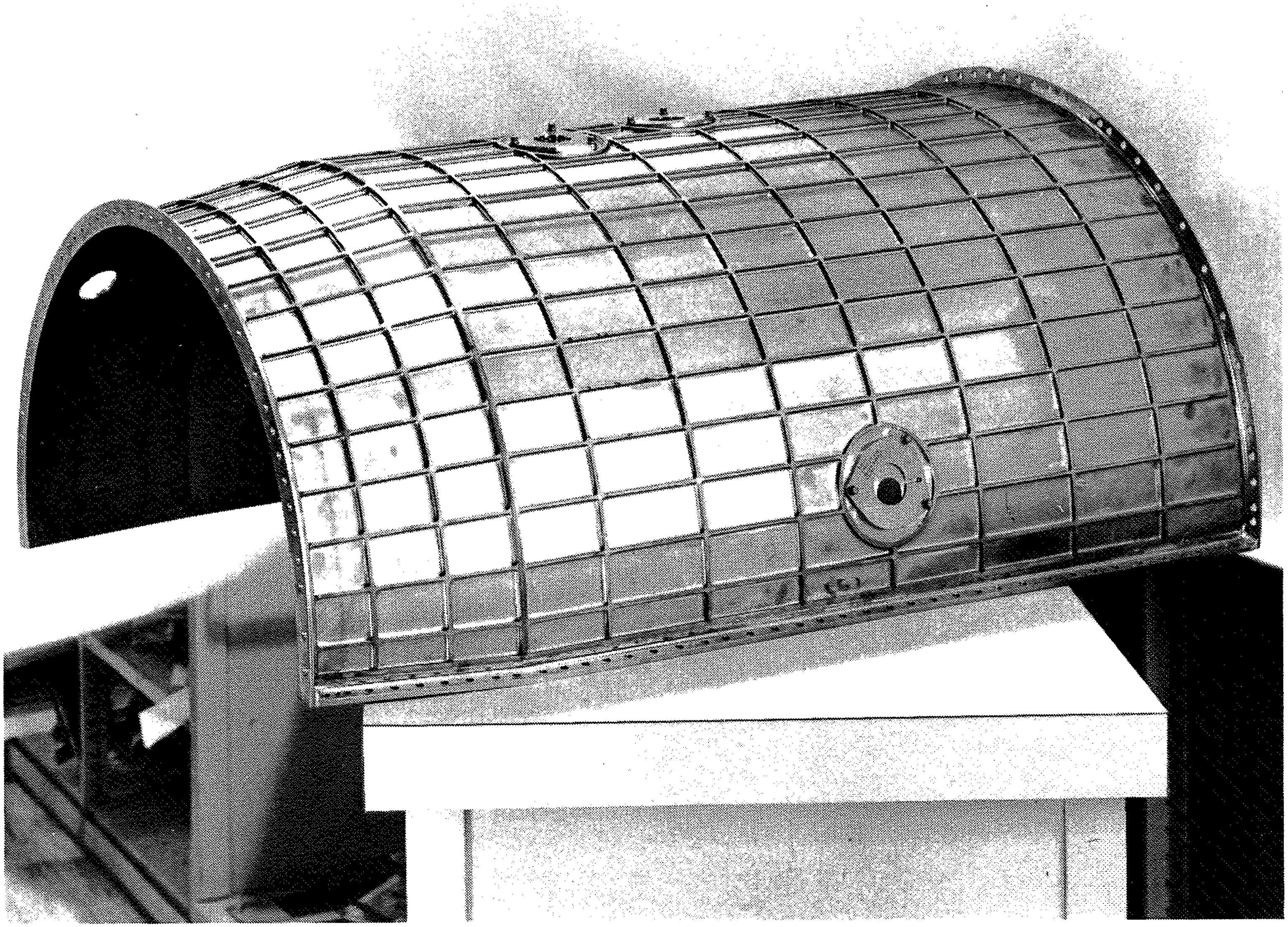

Figure 3. Upper Half of Chemically Milled Titanium Outer Duct of F404 Engine.

3.0 APPROACH

This section outlines the approach taken to establish the potential cost and weight benefits that may be obtained through the application of advanced composite materials, primarily graphite/PMR15, to highly loaded major engine structures.

The initial portion of the program was aimed at establishing a source for the graphite/PMR15 material system, defining a process to cure the system, and developing the basic characteristics of the material system. This effort was divided into the following four technical tasks:

Task I - Material and Process Development

The objective of this task was to select a qualified supplier of the graphite/PMR15 material system and to define efficient autoclave processing parameters for the material system.

Task II - Material Property Generation

Using the process developed in Task I, specimens were made and tested to determine their mechanical properties.

Task III - Buckling Characteristics

A cylindrical cylinder was designed and tested to determine the buckling characteristics of the material system.

Task IV - Load Input Capability

Since joint areas where concentrated loads are reacted are critical and difficult to analyze, specimens representing typical joint areas were designed, fabricated, and tested to verify their load-carrying capability.

The results of the above work indicated that the material system should be suitable for use in highly loaded engine hardware. Consequently, the decision was made to proceed with the design, fabrication, and test of a fully functional outer bypass duct suitable for use on the F404 engine. The following six tasks were added to the program to accomplish this objective.

Task V - Mission Thermal Cycle Testing

Mission profiles of the F-18 were examined, and the duct temperature versus time was calculated. The most critical temperature variation was selected and used in conducting a thermal cycling test of a sample panel. After the thermal testing, specimens were removed from the panel and mechanically tested to determine if any property degradation occurred due to the thermal exposure.

Task VI - Material Design Criteria

A comprehensive test program was conducted to establish mechanical and physical properties of the material system for use in the duct design. Environmental testing was also conducted to obtain thermal oxidation, freezing, cyclic salt spray, erosion, and fluid immersion data.

Task VII - Final Design

Utilizing the data generated in Tasks V and VI, a final design of the F404 composite outer bypass duct was prepared.

Task VIII - Subcomponent Tests

Subcomponent test specimens, representing key areas of the F404 outer duct were fabricated and tested to verify the analytical results.

Task IX - Design and Fabricate Tooling

Based on the final design drawings issued in Task VII, tools were designed and fabricated for use in building a full-scale outer duct.

Task X - Duct Fabrication and Test

Utilizing the tooling fabricated under Task IX, a full-scale duct was fabricated. This duct was proof pressure tested and then installed and run on an F404 factory test engine.

The results of the above effort proved very successful, demonstrating that the use of advanced composites in this application would result in significant cost and weight savings and that the composite duct was structurally and functionally adequate for use on the F404 engine. Based on this experience, one area of further improvement was identified; this area concerned the design of the duct flanges. To explore this potential for improvement, the following task was added to the program.

Task XI - Composite Flange Development

The objective of this task was to develop integral composite forward and aft circumferential end flanges to replace the riveted-on titanium end flanges used in the original version of the composite duct. Representative subcomponents were designed, fabricated, and tested to verify the design concept. A complete duct was then fabricated, incorporating the composite flange design. This duct was then subjected to extensive static testing to determine its strength, relative to design goals.

All of the above efforts showed that the application of the graphite/PMR15 material system to outer bypass ducts would result in significant weight and cost advantages over titanium ducts. It was then desired to determine if these same advantages could be obtained by using this material in other, more complex, portions of the engine. To investigate this possibility, the following task was added to the program.

Task XII - Fan Case and Vane Development

The objective of Task XII was to develop a graphite/PMR15 version of the F404 fan stator case assembly, including the stator vanes, as well as the stator case. The vane attachment techniques and containment requirements were integrated into the design. Critical components and attachment areas were fabricated and tested as subcomponents. A design of the stator assembly was developed and a cost/benefit analysis conducted.

The completion of Task XII marked the end of this program. The following sections of this report present the results of this effort. No attempt has been made to relate the work to specific task structure, since it seemed better to present the results in a more narrative manner.

4.0 TECHNICAL DISCUSSION - COMPOSITE BYPASS DUCT

This section presents the technical discussion of the work performed to evaluate the potential of applying advanced composites, specifically the graphite/PMR15 material system, to major engine hardware. The specific part used for this investigation was the outer bypass duct of the F404 engine. The initial part of this investigation involved the establishment of the design requirements for this component. Based on these requirements, a number of mechanical and physical property development programs were conducted to support the final design and fabrication of a demonstration duct. The results of this effort are discussed in the following paragraphs.

4.1 Design Requirements

In order to understand the duct design rationale, it is necessary to have an understanding of the technical requirements which the duct had to satisfy in the F404-GE-400 engine application. The more significant of these are listed below:

1. Complete interchangeability with existing titanium production bypass duct (this was necessary for introduction on an engine already in production).
2. Temperature range of -54° C (-65° F) to 282° C (540° F).
3. Maximum operating pressure of 496 KPa (72 psi).
4. Proof test pressure of 744 KPa (108 psi).
5. Bending stiffness equal to or greater than previous titanium part.
6. Maneuver loads; the most severe maneuver loading on the duct is described in Table 1 and Figures 4 and 5.
7. Capability to withstand impacts from tool-drop and chain-fall impact without damage.
8. Resistant to degradation from such solvents and fluids, which could contact parts, as:
   - Moisture Saturation and Freezing
   - MIL-H-83282
   - JP-5 Fuel
   - MIL-L-7808 Diester Oil
   - B&B 3100 Engine-Wash Solution
   - Salt Spray.
9. Thermal oxidative stability up to 1000 hours at 288° C (550° F).

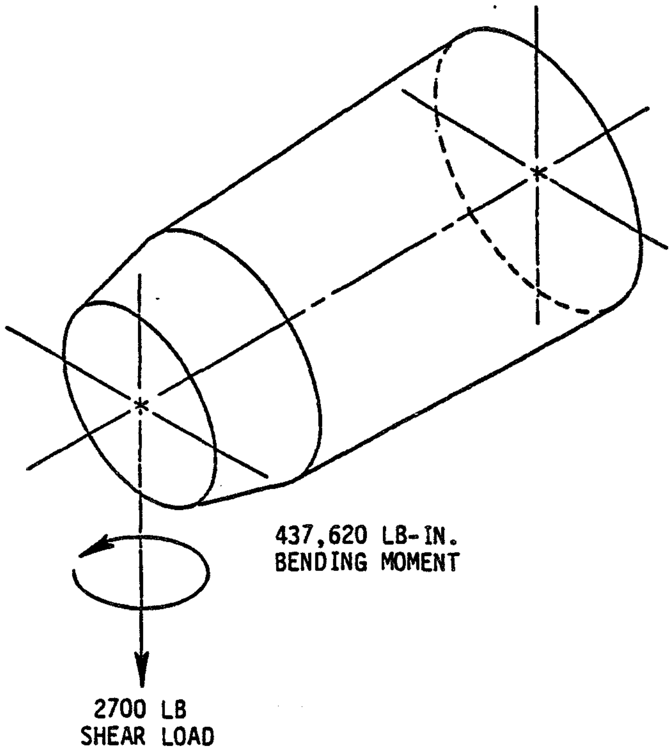

Figure 4. Maximum F404-GE-400 Composite Outer Duct Loads - Forward End.

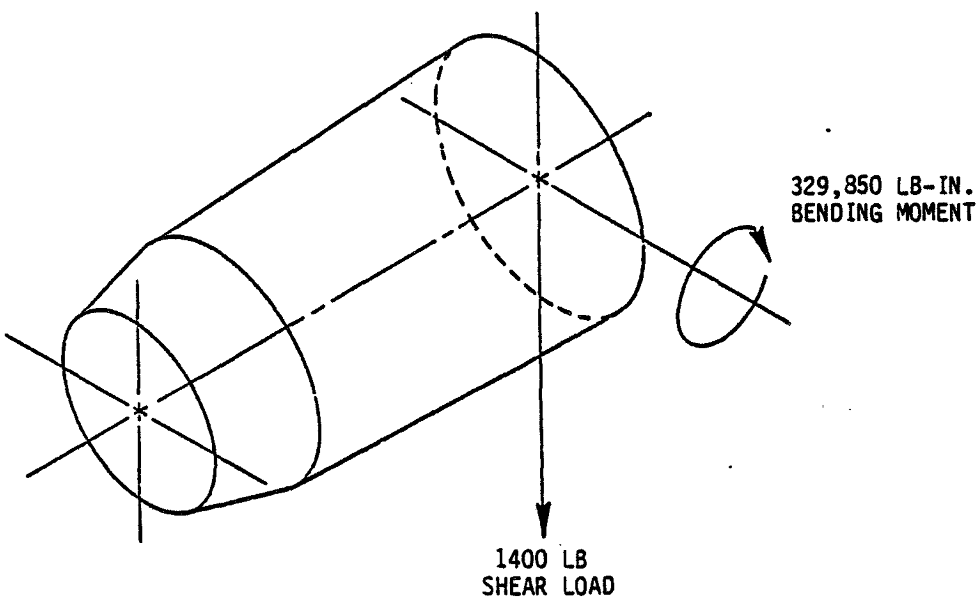

Figure 5. Maximum F404-GE-400 Composite Outer Duct Loads - Aft End.

Table 1. F404 Outer Duct Governing Maneuver Conditions.

Forward End	Aft End
6-g Down	11-g Down
4-g Side	2-g Side
2 rad/sec Pitch	6-g Forward
6 rad/sec^2 Pitch	9 rad/sec^2 Pitch
2 psi - Nozzle	2 psi - Nozzle

10. Actuator load cycling at duct attachment point of 2670 N (600 pounds) for 101,000 cycles.
11. 1000 maximum transient engine temperature cycles with moisture saturation.
12. Buckling margin of 50%.
13. Afterburner load.
14. Engine rotor seizure load.
15. Lower half of duct must support afterburner with upper half of duct removed for servicing core engine.
16. At local attachments, duct body must be stronger than fasteners so failure cannot occur in the more expensive part.
17. Maintain 20% margin above the maximum engine speed for any vibration modes which may be excited in the rotor speed range.
18. Sustain an overpressure of 34.5 KPa (5 psi) without buckling.
19. Resistance to erosion.

4.2 Prototype Design

The prototype design of the F404-GE-400 composite bypass duct is shown on GE Drawing No. 4013266-399 (see Figure 6). This design was based on accomplishments developed under Tasks I through VII of this contract. From a proof pressure test and a static load test of this prototype duct, it was concluded that the number of basic body plies could be reduced from 7 to 6. The recommended structural shell, resulting from these tests, has the following laminate design:

0/0/-45/+45/0/0.

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PLY NO	LAY UP ANGLE	MATL
1 & 2	0°	FIBERGLASS / PMR15
3	0°	GRAPHITE / PMR15
4 & 5	+45°	FIBERGLASS / PMR15
6	-45°	GRAPHITE / PMR15
7 & 8	+45°	FIBERGLASS / PMR15
9 & 10	-45°	FIBERGLASS / PMR15
11	+45°	GRAPHITE / PMR15
12 & 13	+45°	FIBERGLASS / PMR15
14	0°	GRAPHITE / PMR15
15 & 16	0°	FIBERGLASS / PMR15

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TABLE I

HOLE NO.	AK (C13)	AM (H14)	AP (B14)	MIN BUILD-UP THK COMPOSITE MATL
1	240°	2.650	13.361	.117 (9 PLYS)
2	195°	2.650	13.361	.195 (15 PLYS)
3	165°	2.650	13.361	
4	127°30'	2.650	13.361	
5	157°30'	5.300	13.871	.221 (17 PLYS)
6	(187°30')	6.400	14.082	
7	(180°)	6.400	14.082	
8	255°	8.440	14.385	.065 (5 PLYS)
9	127°30'	8.440	14.385	.104 (6 PLYS)
10	225°	11.400	14.451	—
11	213°45'	11.400	14.451	.078 (6 PLYS)
12	157°30'	11.400	14.451	
13	127°30'	11.400	14.451	
14	247°30'	15.580	14.544	.104 (8 PLYS)
15	165°	15.580	14.544	
16	157°30'	15.580	14.544	
17	150°	15.580	14.544	
18	135°	15.580	14.544	
19	105°	15.580	14.544	.065 (5 PLYS)
20	240°	19.715	14.636	(.026) (2 PLYS)
21	225°	19.715	14.636	
22	210°	19.715	14.636	.104 (8 PLYS)
23	195°	19.715	14.636	—
24	(157°30')	19.715	14.636	.104 (8 PLYS)
25	150°	19.715	14.636	
26	127°30'	19.715	14.636	
27	120°	19.715	14.636	
28	202°30'	21.295	14.671	—
29	225°	23.830	14.727	.026 (2 PLYS)
30	210°	23.830	14.727	—
31	165°	23.830	14.727	—
32	105°	23.830	14.727	.065 (5 PLYS)
33	156°23'	25.510	14.764	—
34	143°47'	25.510	14.764	—
35	202°30'	26.195	14.780	—
36	247°30'	27.970	14.819	.026 (2 PLYS)
37	240°10'	27.970	14.819	
38	225°06'	27.970	14.819	
39	202°30'	27.970	14.819	—
40	187°24'	27.970	14.819	—
41	180°	27.970	14.819	—
42	165°	32.460	14.919	.104 (8 PLYS)
43	150°	32.460	14.919	
44	135°	32.460	14.919	
45	120°	32.460	14.919	
46	105°	32.460	14.919	.065 (5 PLYS)
47	247°30'	36.960	15.019	.026 (2 PLYS)
48	239°50'	36.960	15.019	
49	224°55'	36.960	15.019	
50	202°30'	36.960	15.019	.104 (8 PLYS)
51	187°36'	36.960	15.019	
52	157°30'	36.960	15.019	

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AXIAL FLANGE
SECT BG-BG
SECT AH-AH
SECT AG-AG
SECT BC-BC
SECT AB-AB
SECT AD-AD
SECT AA-AA
VIEW BM
VIEW BN
INSTALL INSERT PER
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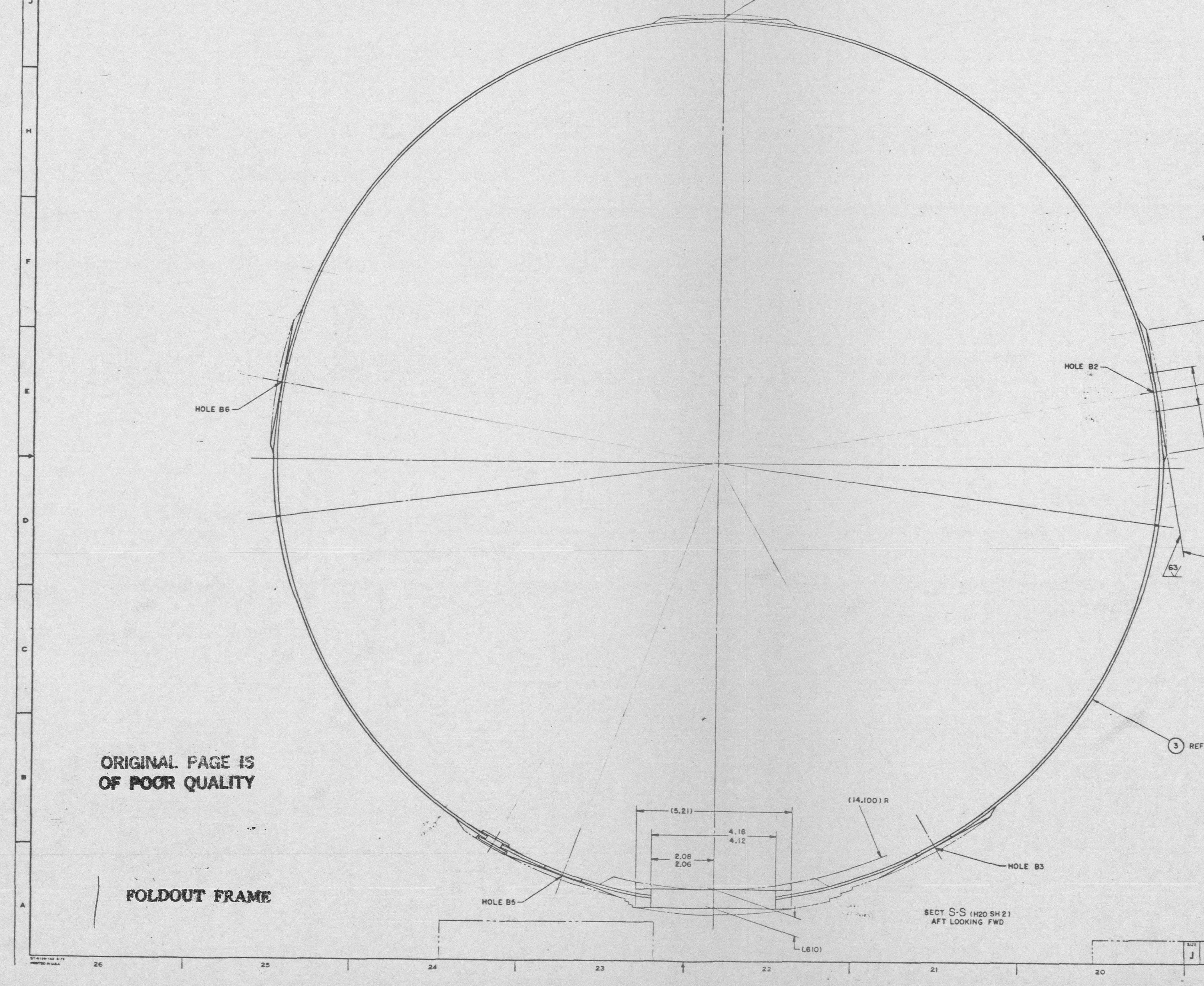

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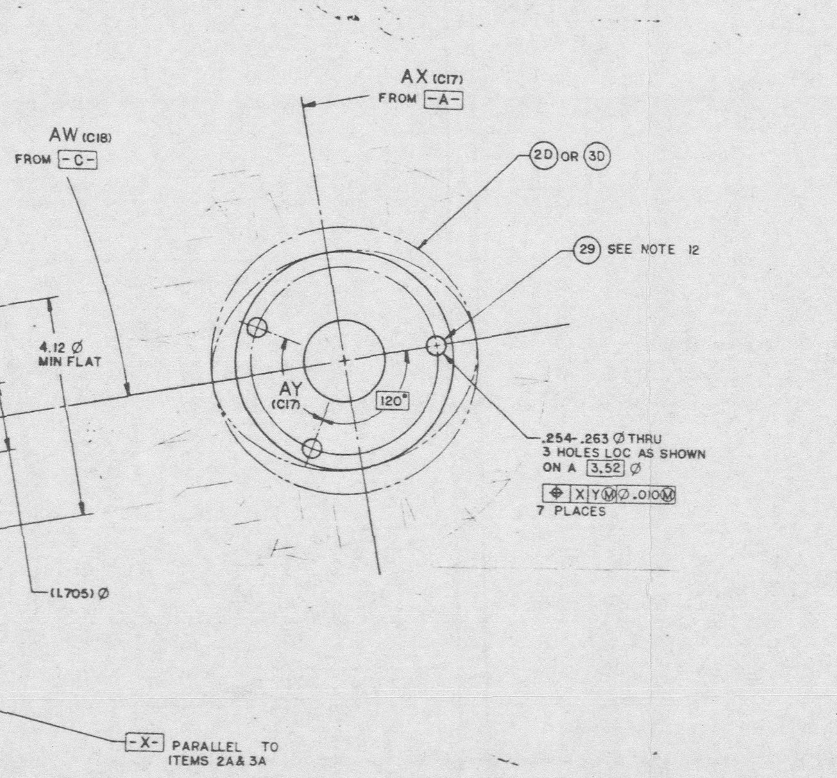

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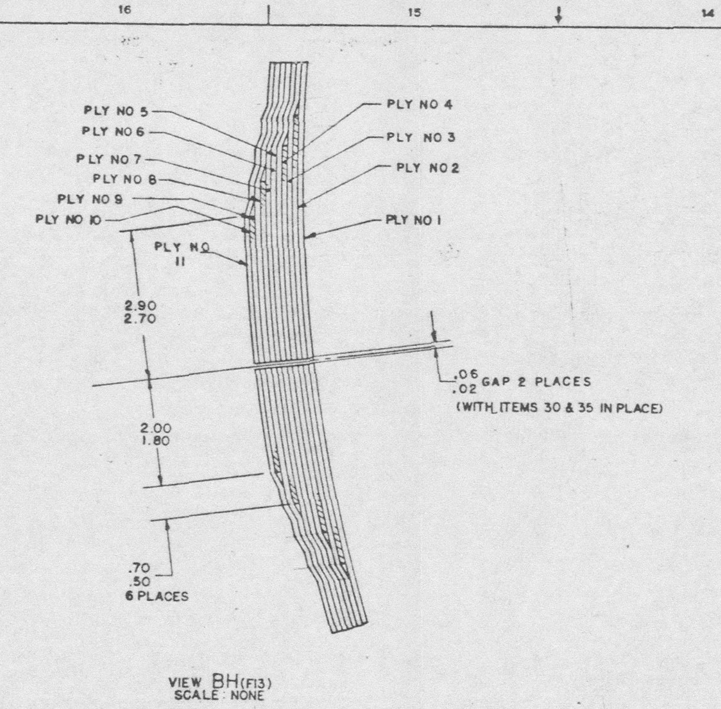
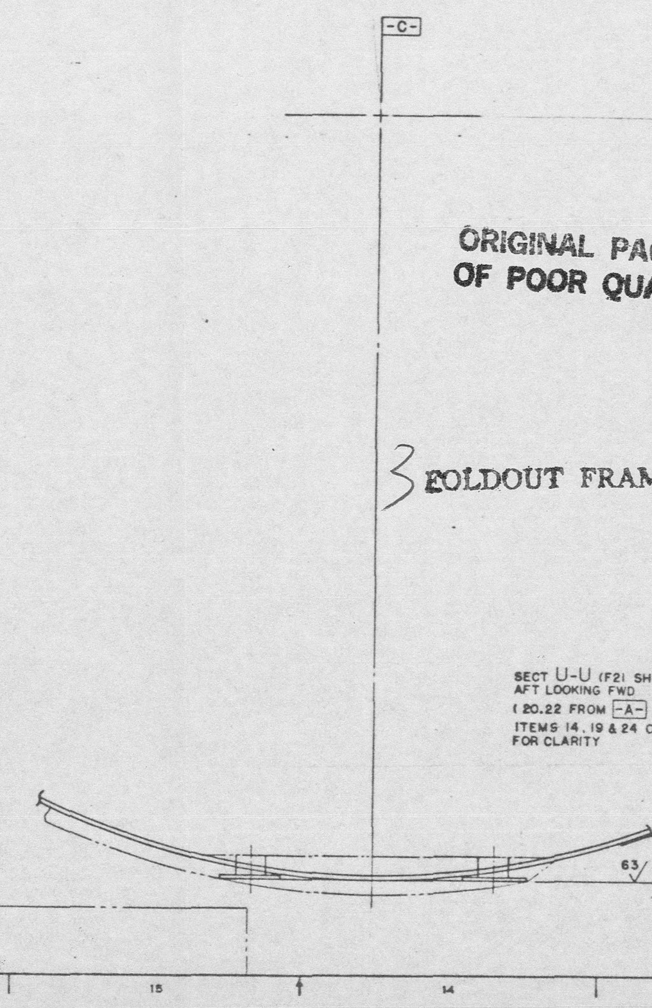
TABLE 2				
HOLE NO.	AW BSC	AX BSC	AY BSC	
B1	0°	23.795	90°	17.605
B2	80°	23.795	90°	17.605
B3	150°	23.745	90°	17.655
B4	180°	34.483	90°	~~6.917~~
B5	200°	23.795	90°	17.605
B6	280°	23.795	90°	17.605
B7	354°48'	17.435	120°	23.965





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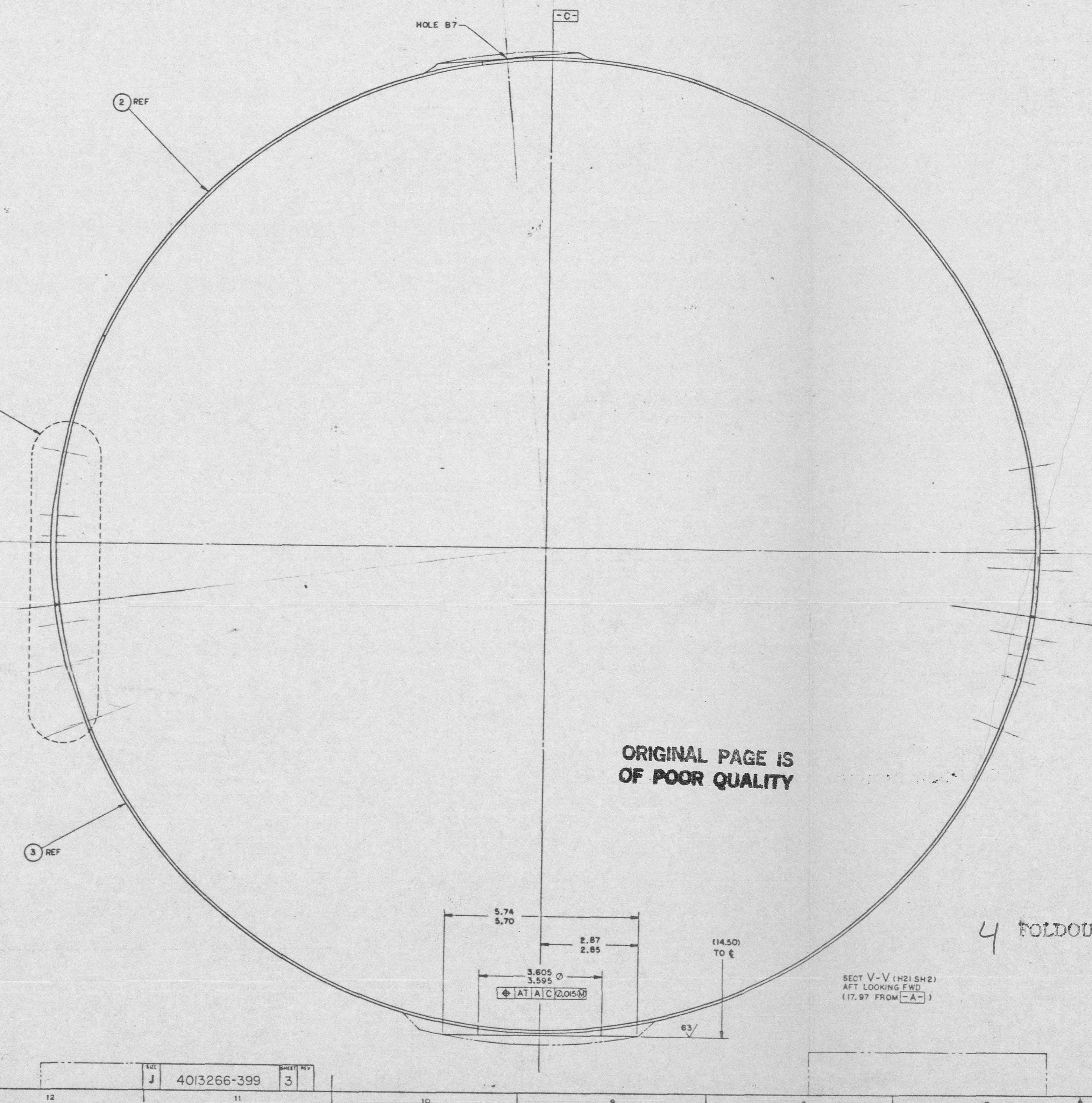

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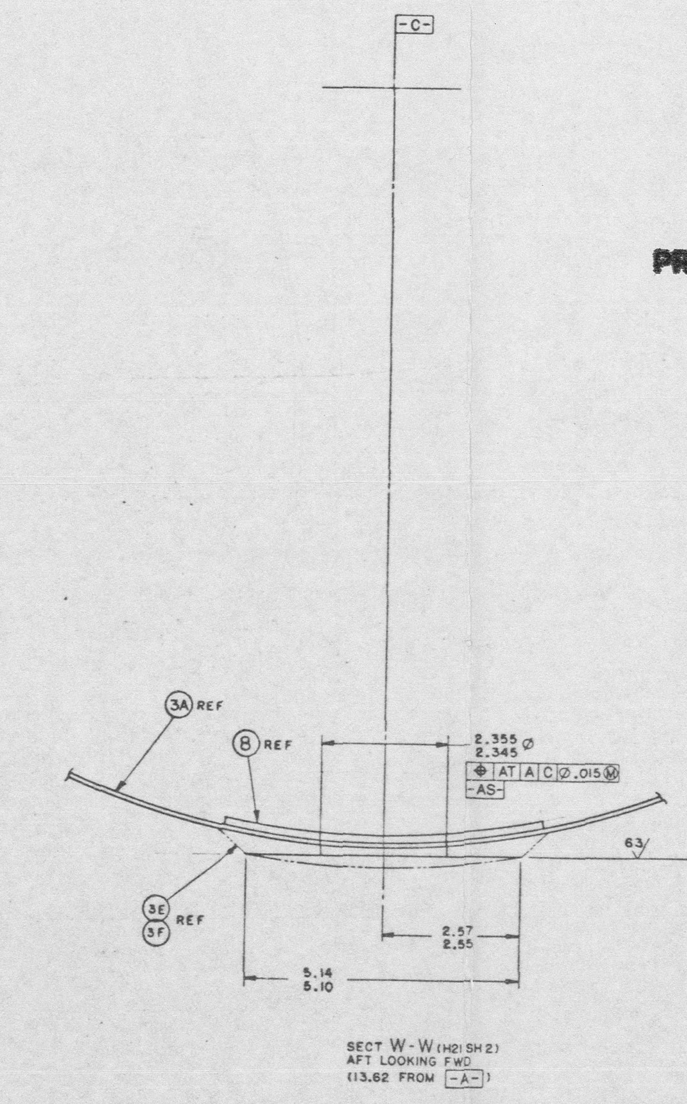

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The angles for each ply are the direction of the warp yarns relative to the longitudinal axis of the part; see Sheet No. 6 of Drawing No. 4013266-399, shown in Figure 6. This laminate design was selected because the duct has high axial shell loads from the large bending moments, as well as high hoop loads from the internal pressure. Each layer of the laminate is a cloth woven from Union Carbide T300 graphite tows (yarns of 3000 fibers) in an 8-harness satin weave (T300-3K-8HS) preimpregnated with PMR15 polyimide resin. The fibers have a Union Carbide UC-309 epoxy sizing finish.

As shown in Figure 6 (Sheet Nos. 1, 3, and 6), the number of layers in the laminate increases from 7 to 11 toward the split-line flanges and end flanges of the part. This is accomplished by interlayering several partial plies (Nos. 2, 4, 8, and 10) in between the main duct body plies (Nos. 1, 3, 5, 6, 7, 9, and 11). All joints in the main body plies are overlapped 0.6 to 1.2 inches so that strength is optimized. Joints in the partial plies are butted to minimize distortion of the main body plies. All joints are staggered so they do not occur at the same location in different layers to maximize duct strength.

The prototype duct was initially designed and built having riveted titanium end flanges and double doubler split-line joints (see Figure 6, Sheet Nos. 1 and 4). The titanium end flanges were riveted to the 11-ply built-up region at each end of the duct shell using two rows of rivets. The rivets were sized and spaced utilizing mechanical joint design criteria from the DoD/NASA Advanced Composites Design Guide. Likewise, the double split-line joint was designed using the mechanical joint criterion.

Under the composite flange development task, Task XI of this contract, the main body plies and the short partial plies bend outward at the split line and axial flanges making an integral composite flange having 14 ply layers. A view of this flange detail is illustrated in Figure 7. A segmented titanium back-up strip was attached with rivets to the fastener side of the composite flanges to provide a bearing surface for the fasteners and to provide support for the laminate in the radius where the shell plies turn outward 90° to form the flanges, thereby preventing delamination in this area.

At fastener locations on the duct and around portholes, the number of plies was increased to provide the same interfaces as those in the production titanium part, for interchangeability of mating hardware. At these locations, reinforcement plies were applied to both the outside and inside of the duct wall. These build-ups were also stepped so that the wall thickness tapers smoothly from thin to thick areas of the duct, thereby reducing stress multipliers. This is very critical in laminate designs of this type, because load is transferred from one layer to another by shear in the resin matrix which is typically much weaker than the in-plane strength of a lamina. All butt joints were removed from the more highly loaded areas of the part, to optimize part strength.

Where it was necessary to achieve very flat or precision surfaces; such as mating surfaces, flanges, and at the high-pressure actuator bracket mounting pad, extra layers were applied to

the laminate to provide machining stock. All hardware (including nut plates, brackets, inserts, fasteners, and flange back-up plates) was designed to be mechanically attached to the duct. Typical hardware attachments are depicted in Figure 6, Sheet No. 2 (Zones C6, C9, B15, H16, and C26); Sheet No. 4 (Zones H8 and H9); and Sheet No. 5 (Zones D3, H11, H14, E16, C17, and H17).

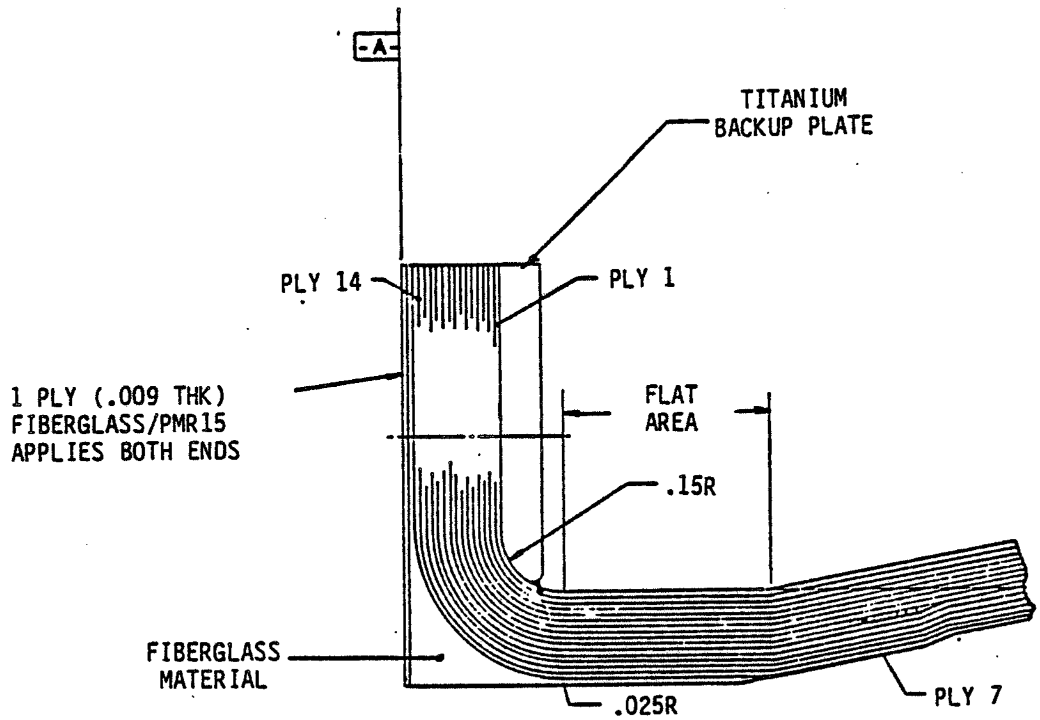


Figure 7. Integral Composite Flange Cross Section with Titanium Back-Up Plate.

To prevent galvanic corrosion, all parts which come in contact with the graphite are made of Inconel 718 or Titanium 6-4, which have a low electrochemical potential with graphite, or they are insulated from the graphite with a layer of glass cloth/PMR15, which is cured with the part.

To provide for attaching such configuration hardware as tubing brackets and electrical cable clamps to the duct, a special stud assembly was designed which is illustrated in Figure 8. A mating threaded ferrule is assembled to the grommet from the opposite side of the duct wall. After torquing these two parts together, a hole is drilled through the flange of the ferrule, the duct, and the flange of the grommet. A flush-head rivet is then installed to lock the assembly in place and provide for antirotation.

Figure 9 illustrates the service pad area of the duct located at six-o'clock, where the anti-icing air line, compressor discharge air bleed line, fuel inlet line, pressure lines, and two borescope

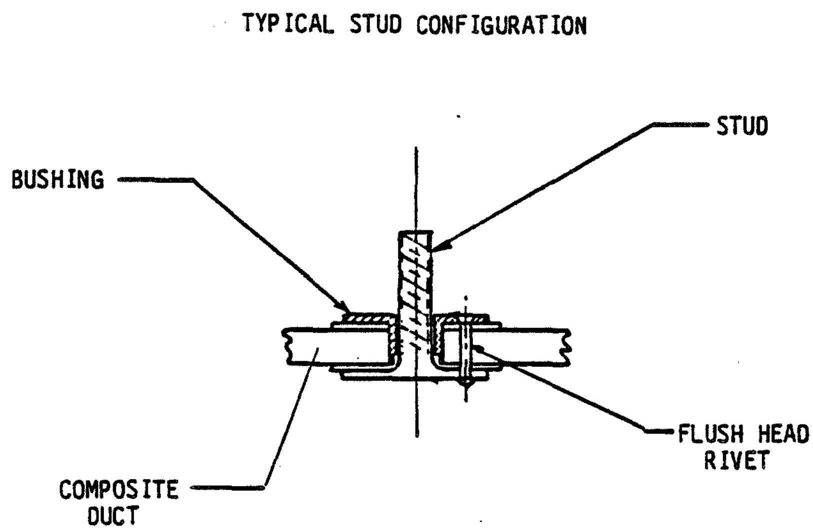


Figure 8. Typical Fastener Design.

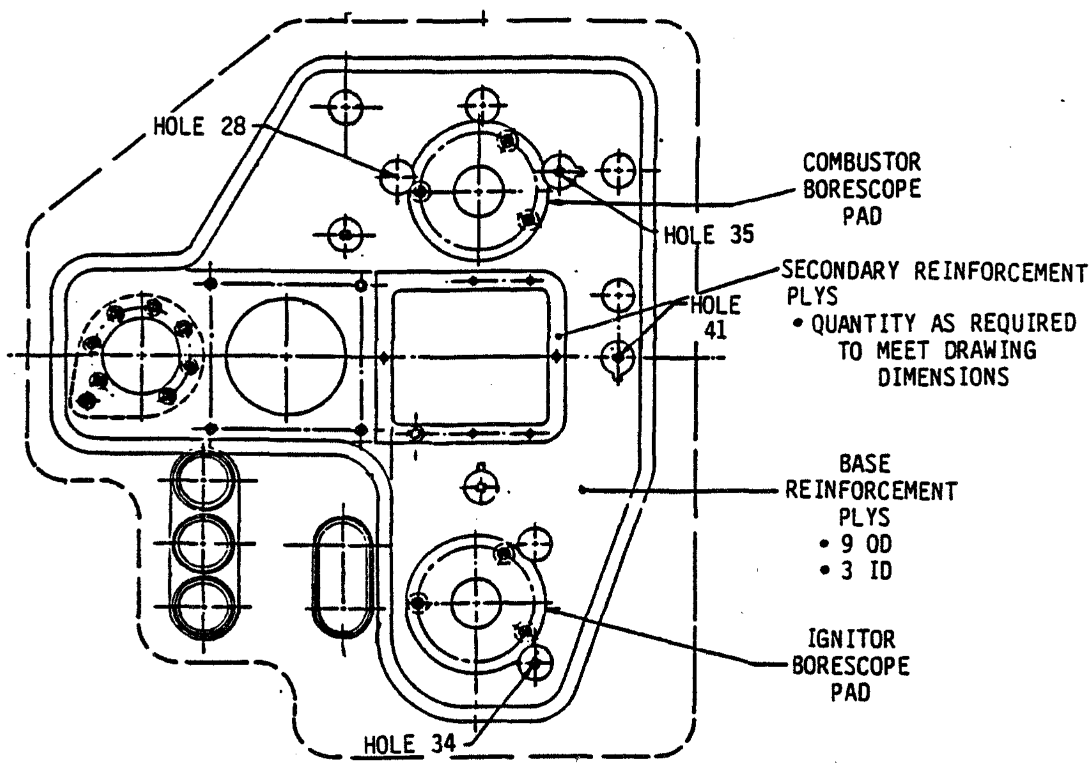


Figure 9. F404-GE-400 Composite Bypass Duct Service Pad Configuration.

access ports are located. The duct wall at this location is reinforced with 13 plies on the outside of the basic 7 plies. The frame around the rectangular porthole has about 50 plies to provide the same dimensional location at the ID (inside diameter) and OD (outside diameter) as the alternate titanium part (other details of this area are shown in Figure 6).

Figure 10 illustrates the detail in the area of the HPVG (high pressure variable geometry) compressor actuator mount. Two of these pads are provided at the forward end of the duct at 1:30 and 7:30 o'clock. Six additional plies are added to both the inner and outer surfaces. There are two machined areas - one for the mounting of a bolted-on HPVG actuator mount, the second for mounting the bearing pad for the radial crankshaft. A cyclic load is applied to the HPVG mount which, in turn, applies a local moment to the shell of the duct. With the reinforcement in this area, the total stresses in the part remain below the allowable design limit. For more detail of this area, refer to Figure 6.

4.3 Duct Analysis

To evaluate the structural capability of the F404-GE-400 composite bypass duct analytically, a finite element analysis was performed. The MASS structural computer code, developed by GE, was utilized for this study. The laminated structure was modeled using the quad plate element which formulates the bending and plane stress properties representing membrane behavior. The analytical model of the duct, with its 840 elements, is illustrated in the various views of Figure 11.

The AC3 point stress analysis program described in the DoD/NASA Advanced Composite Design Guide (prepared by North American Aircraft Operations of Rockwell International Corporation under U.S. Air Force Contract F33615-78-C-3203, July 1983) was used for the composite duct. For the 7-ply region of the duct, the AC3 program yielded the following orthotropic material properties:

- E1 = E2 = 5.22 x 10E7 KPa (7.58 x 10E6 psi) (Tensile Modulus)
- G12 = 1.64 x 10E7 KPa (2.38 x 10E6 psi) (Shear Modulus)
- U12 = 0.263 (Poisson's Ratio).

The above model was used to analyze the duct stresses under the maximum internal pressure of 500 KPa (72 psi). The analysis was also run with a 37 KNm (330,000 in-lb) moment at the aft end and a 49.5 KNm (440,000 in-lb) moment at the forward end.

The most severe combined load case on the duct is comprised of the following loads being applied simultaneously:

- 54.7-KN (12,300 lb) axial load (F2) from the afterburner
- 49.5-KNm (440,000 in-lb) moment about the vertical axis at the forward end of the part (My)

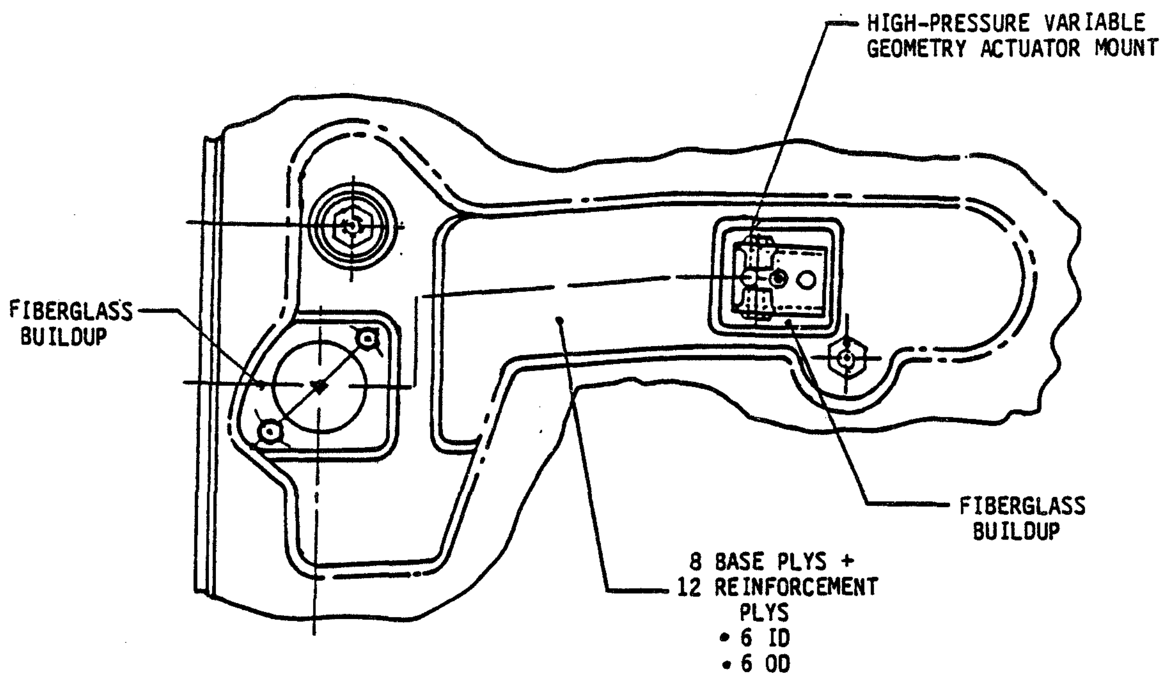


Figure 10. Detail Around High Pressure Variable Geometry Actuator Mount Pad.

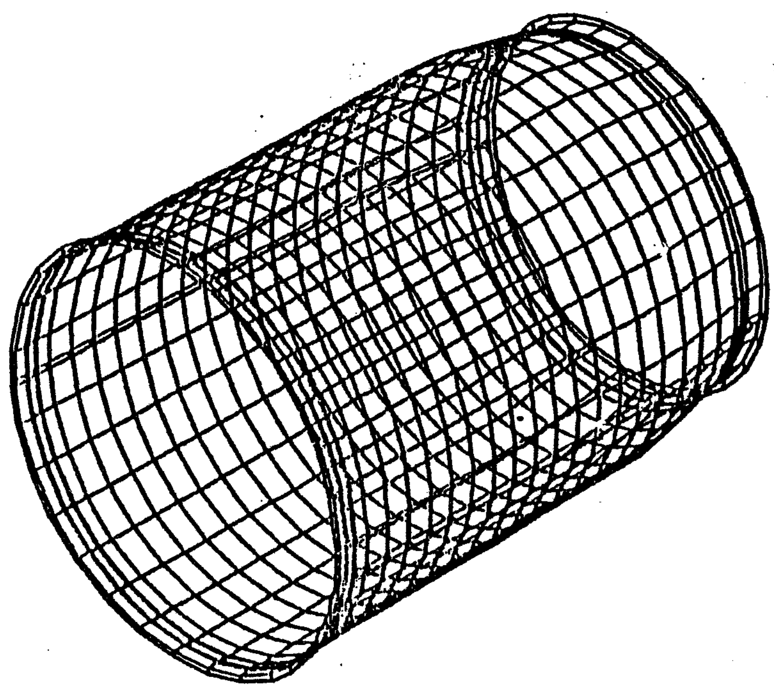


Figure 11. F404 Composite Duct Plate Model.

- 12-KN (2700 lb) shear load at the forward end of the duct (Fy)
- 496-KPa (72 psi) internal pressure.

The maximum element tensile stress in the composite portion of the duct for the cases analyzed is 140 MPa (20.3 ksi), compared to the 367-MPa (53.3 ksi) tensile strength of the laminate. The maximum compressive stress in the composite duct body is 83 MPa (12.0 ksi), compared to the 339-MPa (49.2 ksi) compressive strength and a 123-MPa (17.9 ksi) critical buckling strength of the laminate. More comprehensive results are presented in Table 2.

To correlate the results of the finite element analysis of the duct with the material design strength properties obtained from the 4-ply test coupons, an AC3 point stress analysis of a coupon test specimen was run. Test specimens were laminated and cured with the same process and quality requirements as the duct. The test specimen layup is shown in Figure 12. At the minimum section of the coupon, the laminate design is 0/+45/-45/0, with the angles being the direction of the warp relative to the load which is applied to the specimen. Additional plies are interlayered into the specimens both to reinforce the ends of the specimens where they are attached to the loading device, and also, to eliminate stress concentrations and end effects from the attaching clamps.

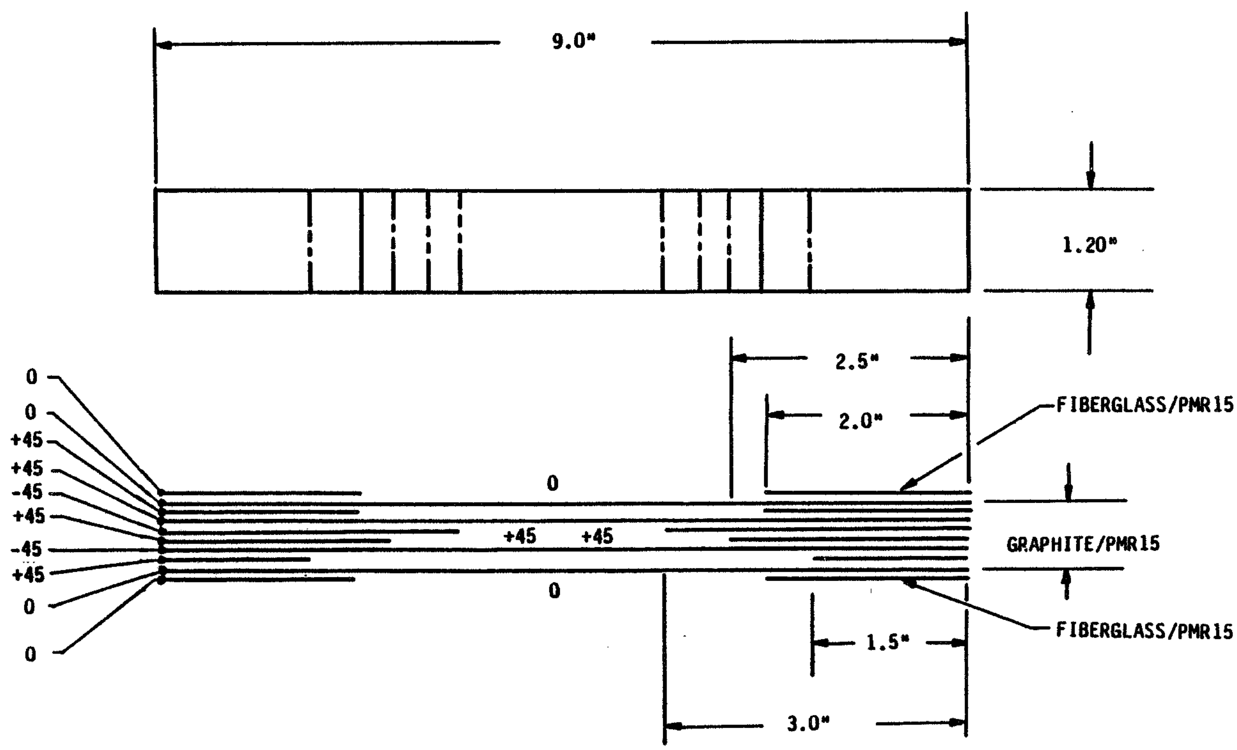


Figure 12. T300-3K-8HS/PMR15 Graphite/Polyimide Material Test Coupon Lay-Up.

Table 2. F404 Composite Outer Duct Stress Results (Mass Plate Analysis).

	ULT. STRESS (KSI)	ALLOWABLE (KSI)	M.S.
MAX FWD MANEUVER X 1.5 (R.T.)			
TENSILE	10.25	53.3	4.20
COMPRESSIVE BUCKLING	7.0	16.6	1.37
SHEAR	4.7	8.20	0.74
MAX AFT MANEUVER X 1.5 (R.T.)			
TENSILE	13.1	53.3	3.07
COMPRESSIVE BUCKLING	12.0	17.9	0.49
	11.6	16.6	0.43
SHEAR	2.8	8.20	1.93
MAX OPERATING PRESSURE X 1.5 (R.T.)			
TENSILE	20.3	53.3	1.63
COMPRESSIVE BUCKLING	1.3	12.6	8.7
SHEAR	1.0	8.20	7.20
MAX COMBINATION (543°F)			
TENSILE	29.9	52.75	0.76
COMPRESSIVE BUCKLING	12.9	23.8	0.84
	7.4	12.6	0.70
SHEAR	4.1	5.75	0.40
MAX OVERPRESSURE			
COMPRESSIVE BUCKLING	1.2	2.23	0.86
H.P.V.G. ACTUATOR			
SHELL BENDING	3.2	16.7	4.22
TORSIONAL ROTOR SEIZURE			
SHEAR BUCKLING	6.5	11.8	0.83

Figure 13 shows the allowable ultimate design strength of the material versus temperature. Over the part-temperature range of interest, it can be seen that the 95% confidence, 99% exceedence minimum ultimate tensile strength is 289 MPa (42,000 psi).

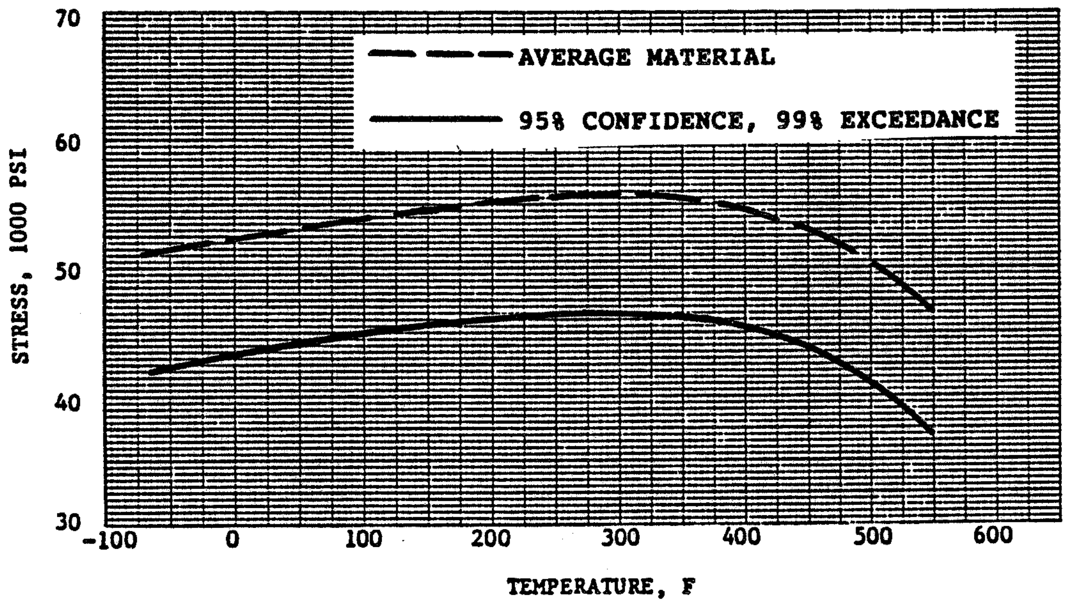


Figure 13. Ultimate Tensile Strength of T300-3K-3HS/PMR15 Composite Laminate.

A further, more detailed, stress analysis was performed for the split-line flange of the duct, which is the most highly loaded portion of the part. The ANSYS finite element model used for this analysis is shown in Figure 14. The most severe loading condition for the split-line flange is the maximum pressure loading of 496 KPa (72 psi). The highest element stresses for this case are shown in Figure 15. The highest individual stress is 282 MPa (41 ksi), versus the 840 MPa (122 ksi) allowable, providing a safety factor of 3.0. Alternatively, using the average material properties from the above-mentioned AC3 program, the maximum stress is 123 MPa (17.8) ksi versus the 289 MPa (42 ksi) allowable, yielding a safety factor of 2.4.

4.4 Material Development and Evaluation

In support of this composite duct program, the following had to be initiated:

- Material testing
- Evaluation of the effect of defects on material properties
- Process optimization
- Preparation of material specifications.

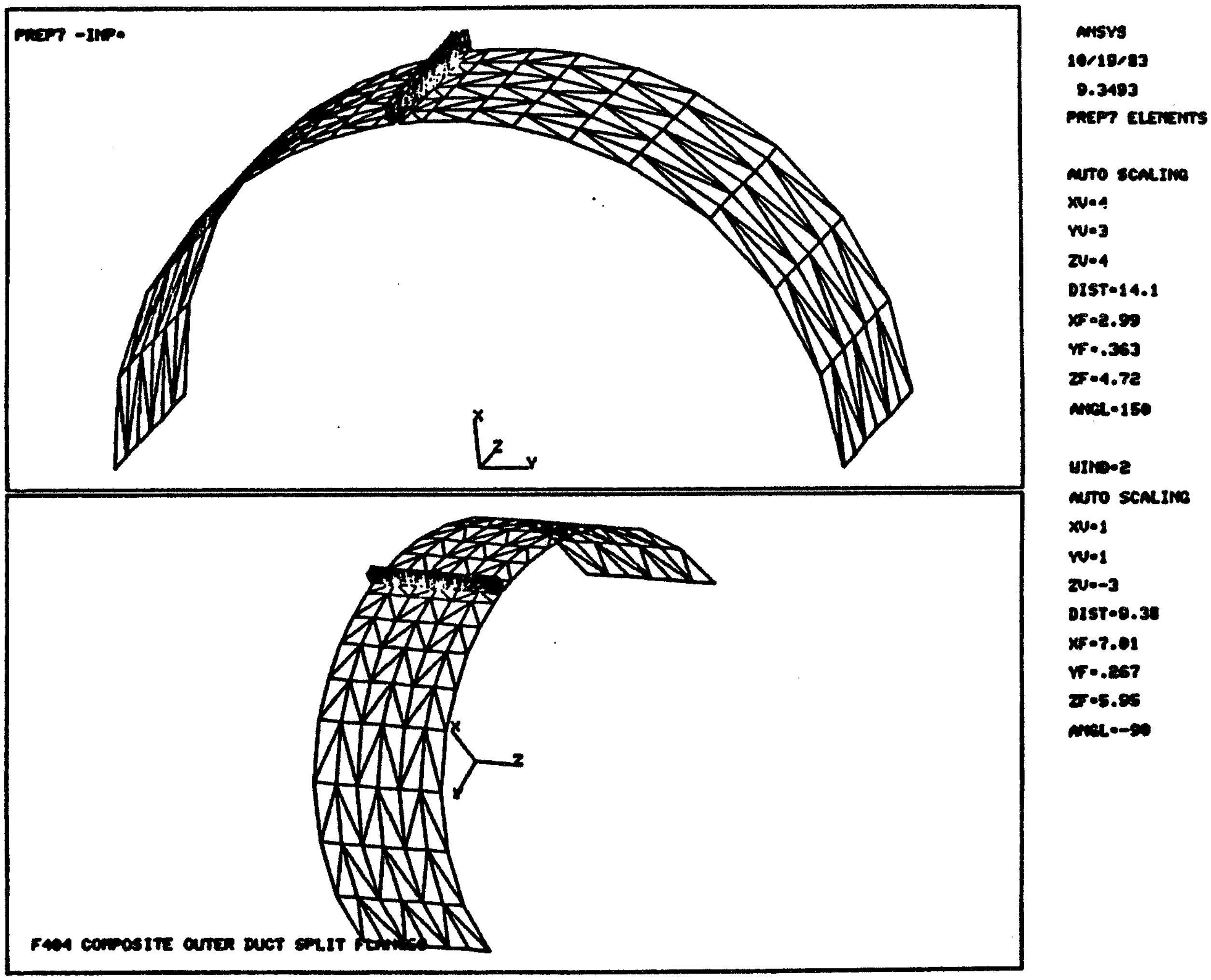


Figure 14. ANSYS Finite-Element Model of Split-Line Flange.

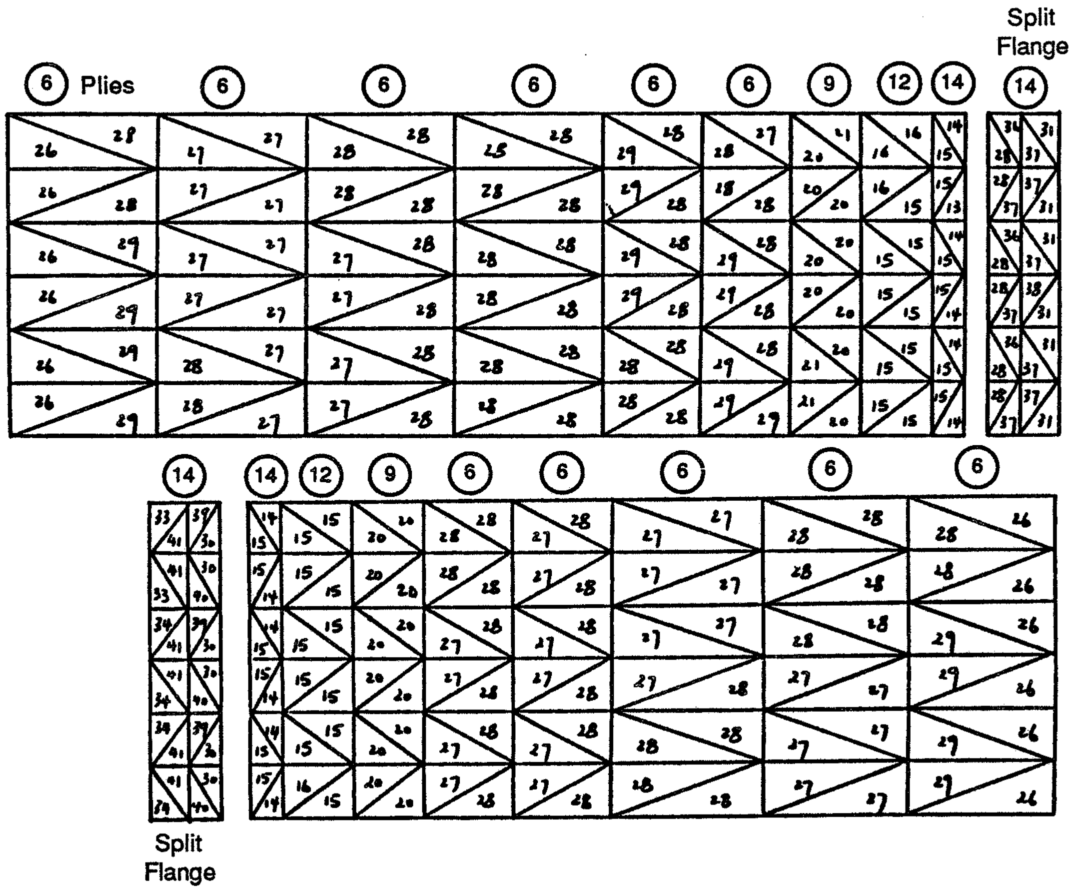


Figure 15. Highest Element Stresses in ANSYS Laminated Flange Model for 72-psig Loading.

All material data obtained on this program was based upon Union Carbide Corporation T300 graphite fibers and U.S. Polymeric prepreg, the same as those used in the manufactured ducts.

4.4.1 Material Specifications and Quality Control

The following GE Aircraft Engines specifications were prepared to define and control the raw material utilized in the development of the F404-GE-400 composite bypass duct.

- 4013240-802 - Woven Graphite Fabric PMR15 Polyimide Resin
- 4013240-871 - Woven Fiberglass Fabric PMR15 Polyimide Resin

These specifications are included in Appendix A. They provide the limits for storage and the required properties which the cured laminate must meet for both the warp and fill directions. Provided also are the chromatogram signature for the material and the curing procedure for the laminate.

4.4.2 Material Characteristics Development

Following are material properties obtained over temperatures ranging from -54° C to 288° C (-65° F to 550° F), with sufficient samples to generate statistical data to determine design properties based upon 95% confidence that 99% of the samples exceed this minimum value:

- Ultimate tensile strength
- Tensile modulus
- Ultimate compressive strength
- Compressive modulus
- Tensile fatigue (HCF): load, NF
- Compressive fatigue (HCF): load, NF.

Property curves for these are included in Appendix B. However, the following properties have additionally been determined:

1. **Short Beam Shear Strength** - See Page 5 of Specification 4013240-802, contained in Appendix A.
2. **Rail Shear Strength** - See Appendix B.
3. **Impact Strength** of the duct laminate was tested under both a simulated tool drop and chain-full impact, as demonstrated in Figure 16 (Views A and B), without any damage, external or material.
4. **Thermal Conductivity** was measured for the duct laminate, with results presented in Table 3.

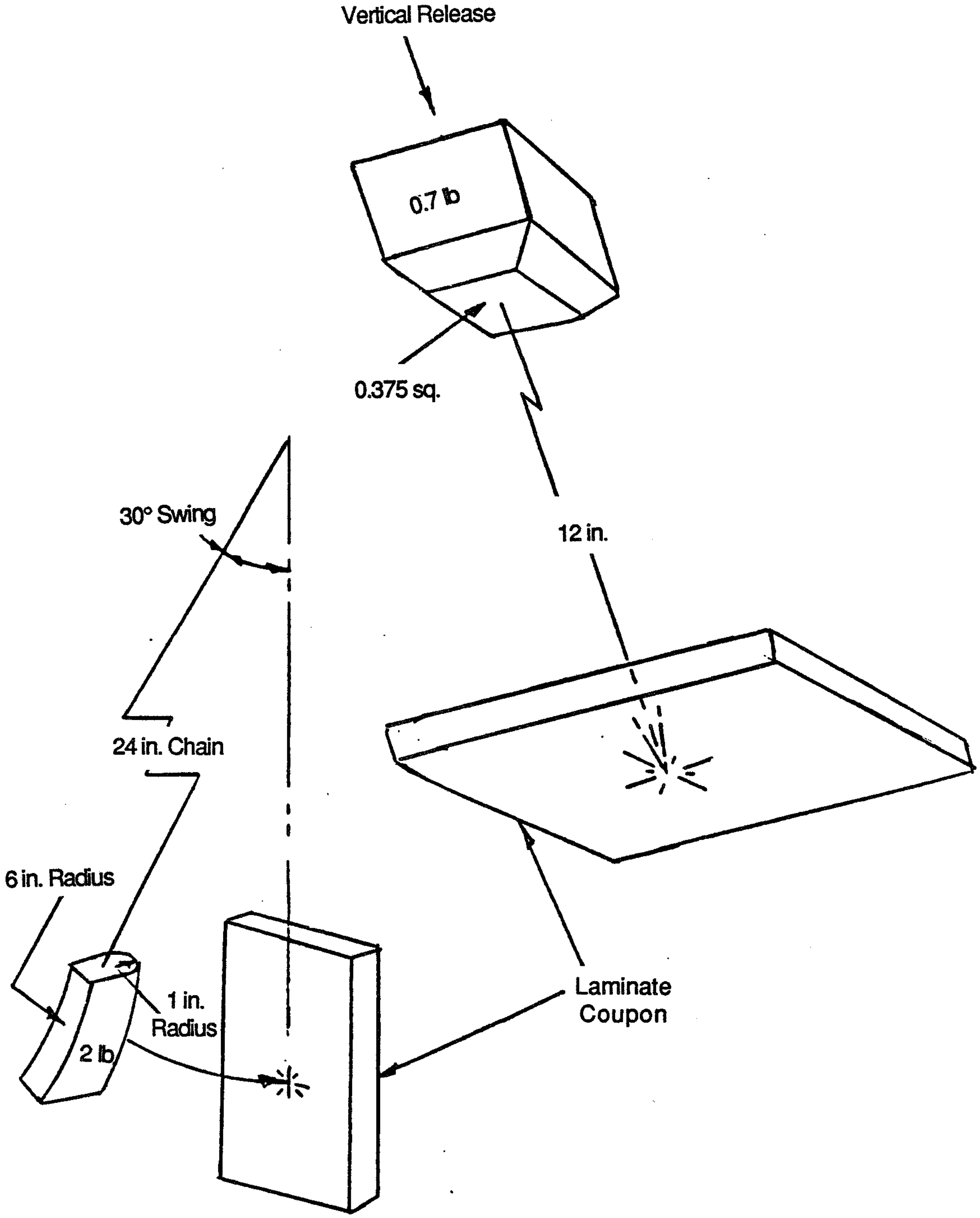


Figure 16. Impact Tests Performed on Duct Laminate.

Table 3. Laminate Thermal Conductivity of 8-Ply (0°) T300-3K-8HS/PMR15.

Lot No.	Test Temperature	Thermal Conductivity (Btu in hr/ft^2/°F)
USP G9516	-65°F	2.32
	75°F	4.09
	212°F	5.033
	350°F	5.66
	550°F	6.26
Test Specimens:	8 Ply - 0.106 x 2.0 x 2.0	
Method:	Guarded Comparative Longitudinal Heat Flow Technique. (ASTM E-27)	

5. **Thermal Oxidative Stability** of the duct material was measured, and the results are shown in Table 4.

6. **The Coefficient of Linear Thermal Expansion** was measured; the results are shown in Table 5.

7. **The Flexural Strength and Modulus** were tested with and without moisture saturation; this data is tabulated in Appendix B.

8. **1000-Hour Creep Rupture** data is provided in Appendix B for material from two suppliers.

9. **Density** of the T300-3K-3HS/PMR15 laminate is 1.55 gm/cc at about 2% average porosity.

10. **The Tensile and Fatigue Strength of a Damaged Laminate Sample** was obtained. Two different 4-ply samples were tested: one with a scratch 0.0635 to 0.1524 cm (0.025 to 0.060 inch) wide by 0.0254 to 0.033 cm (0.010 to 0.013 inch) deep normal to the load, the second with a scratch at 45° to the load direction. The fatigue test was run on the 45° defect sample only since the tensile test showed little difference in the two defects. The sample is shown in Figure 17, with test results in Table 6.

The following material tests were conducted to demonstrate the capability of the material to withstand all the possible environmental influences which could affect the duct in service.

1. **Absorption of Moisture** - See Figure 18.

2. **Water Saturation and Freezing Test** - Several laminate specimens were immersed in water at RT (room temperature) for 100 hours, were then frozen to

Table 4. Thermal Oxidative Stability of T300-3K-8HS/PMR Composite Laminate, 4-Ply (0°/±45°/0°), with Exposure at 72 psia.

Lot/ Spec No.	*Hours Exposed	Exposure Temperature (°F)	Weight Lost %	Weight Lost Average	75°F Tensile Strength psi	75°F Tensile Strength Average	75°F Modulus (psi x 10^6)	Average
BT25			.015		56,040		6.5	
BT26	1000	350°F	.013		61,970		6.9	
BT27			.005	.011	59,330	59,113	6.8	6.7
BT26			.002		56,040		6.7	
CT18	500	350°F	.098		61,660		7.1	
DT17			.074	.058	59,240	58,980	6.8	6.9
BT39			.004		50,540		6.9	
CT18	100	350°F	.14		65,010		6.8	
ET18			.10	.081	65,950	60,500	7.1	6.9
B40			.001		54,000		7.1	
ET19	50	350°F	.07		68,020		7.5	
DT18			.003	.025	58,210	60,076	6.6	7.1
CT20			0.85		52,520		6.6	
DT19	500	450°F	0.78		47,870		6.7	
ET19			0.64	.76	53,000	51,130	7.1	6.8
CT21			.32		62,610		6.8	
DT20	100	450°F	.27		60,500		6.8	
ET20			.17	0.25	62,870	61,993	6.8	6.8
BT41			.13		49,310		6.9	
CT22	50	450°F	.27		63,500		7.0	
ET21			.13	0.18	60,310	57,707	7.0	7.0
BT42			1.55		28,860		6.4	
DT21	100	550°F	.99		37,210		6.9	
ET22			.87	1.14	39,850	35,306	6.8	6.7
BT43			.73		42,310		6.4	
DT22	50	550°F	.75		47,160		6.6	
CT19			.67	.72	51,340	46,937	7.0	6.7

* Specimens preconditioned 4 hours at 250°F.

Table 5. **Coefficient of Linear Thermal Expansion of T300-3K-8HS/PMR15 Laminate, 6-Ply ($0_2°/\pm45°/0_2°$) T.**

Lot No.	Number	Resign Content Weight (%)	Panel Void (%)	Density (gm/cc)	Spec No.	Coeff of Linear Thermal Expansion (in/in/°F x 10^{-7}) Temperature Range: -65°F to 74°F to -65°F	74°F to 350°F to 74°F	74°F to 450°F to 74°F	74°F to 550°F to 74°F
USP G9456 (A)	40	26.72	3.38	1.56	1A	6.69	5.06	7.42	8.79
USP G9515 (B)	G15-2/6	28.18	2.35	1.57	2B	10.00	5.05	7.41	8.78
FERRO 12072 (C)	F72-1/6	30.78	1.56	1.57	3C	6.68	6.73	7.40	8.77
FERRO 12073 (D)	F73-2/6	31.33	1.03	1.57	4D	10.00	6.73	8.65	9.76
				Average		8.34	5.89	7.72	9.03

Test Specimens and Tests per ASTM D696-70.

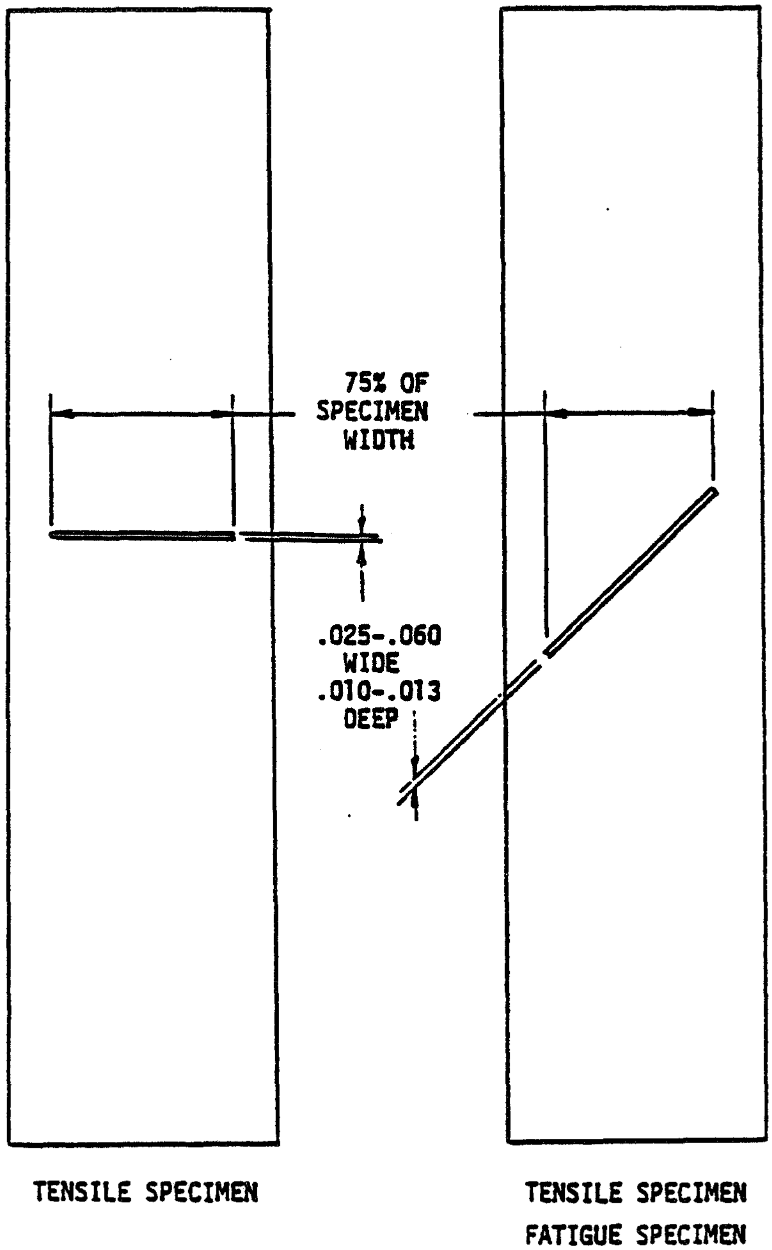


Figure 17. Accidental Damage Specimen - Made from Tensile/Fatigue Specimen.

Table 6. Tensile/Fatigue Strength of Accidental Damage Specimen, Tested at Room Temperature.

Lot No.	Panel No.	Panel Resin (% wt)	Panel Void (%)	Panel Density (gm/cc)	Spec No.	Tensile Strength (psi)	Tensile Modulus (psi x 10^6)	Damage Type
					ET28	46,470	6.16	90° cut .013 inch deep .025-060 inch wide, at midspan.
USP G9516	G16-3Y	28.6	0.1	1.58	ET29	46,640	6.84	45° cut .013 inch deep, .025-.060 inch wide, at midspan.
					ET35	Stress Level (PSI x 10^3)	Fatigue[1] Cycles	
						20	10^7	

Specimen Type: Yokel
Laminate Material 4 ply $(0°, \pm45°, 0°)_T$ T300-3K-8HS/PMR15
(1) R = 0.1
Axial - Axial Fatigue at 30 cps.
Runout (10^7)
Note: Average static tensile strength at 73°F of T300-3K-8HS/PMR15 (0°, ±45°, 0°) is 56,332 psi without damage.

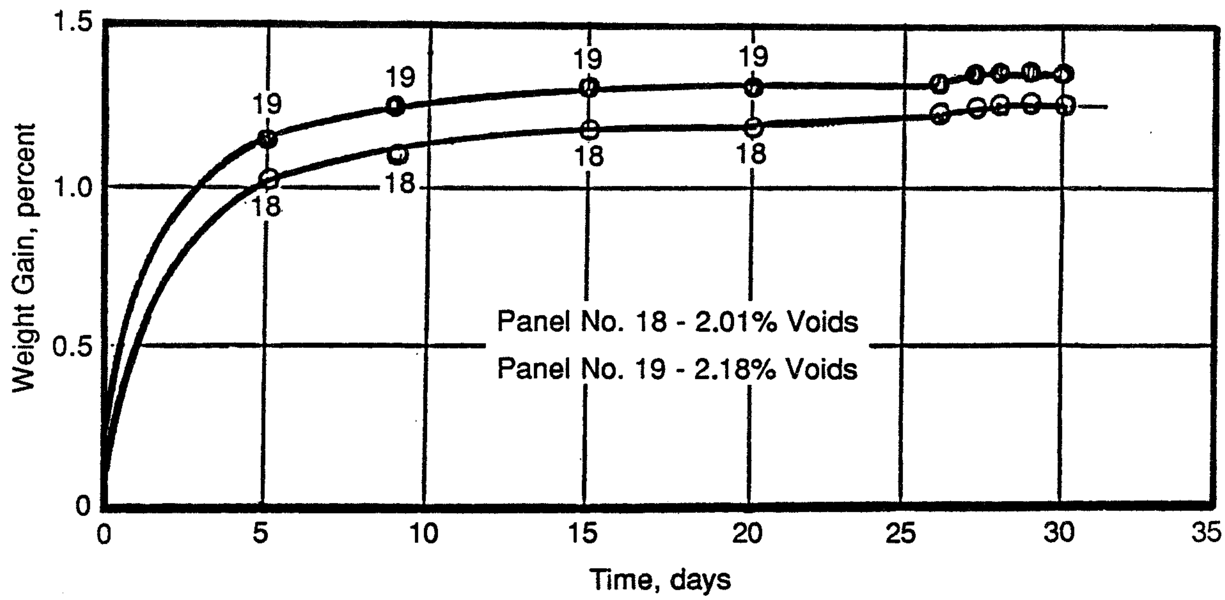


Figure 18. Moisture Absorption of T300-3K-3HS/PMR15 at 180° F and 98% Relative Humidity.

-54° C (-65° F) and held there for 30 minutes. After the panels returned to room temperature, examination of the material both microscopically and by ultrasonic C-scan showed no change from control specimens, which had not been frozen.

3. **Erosion Tests** - Table 7 lists the results of the erosion tests to which the material was subjected.

4. **Cyclic Salt Spray** - Three tensile specimens were subjected to a 1000-hour cyclic salt spray followed by 5 days of baking at 177° C (350° F) in air, repeated for a total of 1000 hours. At the end of the test, the specimens were tensile-tested, with no change in properties from control samples which did not receive the salt spray cycling.

5. **Fluids Immersion Tests** - Laminate samples were immersed in the following fluids for 100 hours:

   - MIL-H-83282 at 93.3° C (200° F)
   - JP-5 at 93.3° C (200° F)
   - Diester oil at 93.3° C (200° F)
   - B&B-3100 engine cleaner solution (20% B&B 31,000 80% water) at RT.

   Flexural strength tests conducted on these specimens revealed no variance from the unexposed control specimens.

Table 7. Erosion of 4-Ply (0°/±45°/0°) $_T$ T300-3K-8HS/PMR15 Laminate.

Laminate Pre-Conditioning		Specimen No.	Erosivity, E (1) (Index of Erosion)	Average
Control		BF6	36	
		CF6	31	
		DF6	28	31.7(2)
100 Hours 120°F - 95% Relative Humidity		BF2	21	
		CF2	23	
		DF2	22	22.0
100 Hours 200°F MIL-H-83282		BF12	25	
		CF12	26	
		DF12	25	25.3
100 Hours 200°F - JP5		BF18	17	
		CF18	28	
		DF18	26	23.7
100 Hours in 200°F MIL-L-7808 OIL		BF24	32	
		CF24	19	
		DF24	19	23
100 Hours at Room Temperature B&B 3100 and Water		BF30	29	
		CF31	25	
		DF31	20	25
72 psia 350°F	50 Hours	BF40	21	
	100 Hours	DF52	19	
	500 Hours	CF52	21	
	1000 Hours	BF48	25	(3)
450°F	50 Hours	DF54	23	
	100 Hours	DF53	25	
	500 Hours	CF53	30	
550°F	50 Hours	BF41	24	
	100 Hours	CF54	20	
6 Mils Caapcoat II (4)		B44	28	
12 Mils Caapcoat II		DF51	24	
6061 T-6 AL		-	88	

(1) Erosivity - Time to Erode (in seconds) ÷ Depth of the Erosion (in mils).
Number reported is an average of 3 tests on a specimen.
The Erosion test makes use of an S.S. white jet abrader to impinge 274 Al_2O_3 powder on the specimens at an angle of 20° to the surface.
Blasted at 45 psig at room temperature.

(2) This average represents 9 tests ie. 3/specimen x 3 specimens = 9

(3) Average of 2 tests.

(4) Caapcoat white fluoroelastomer Type II coating supplied over GR/PMR15 control specimens by CAAP Co., Inc. P.O. Box 2066, Huntington, Connecticut.

6. **Mission Thermal Cycle Testing** - The objective of this test is to determine the effects of rapid-temperature-rise on a panel made with T300-3K-8HS/PMR15 material. This was done by exposing a panel to the most critical thermal gradient that the material would encounter in the F404 outer duct application. The panel was fully saturated with moisture prior to testing. After thermal cycling, flexural test specimens were cut from the panel and tested. The results of these tests were compared to flexural test results from a panel that had not been thermal-cycled to determine if the thermal cycling degraded the properties of the material.

Two panels of T300-3K-8HS/PMR15 were made for thermal cycle evaluation. These panels, identified as Nos. 18 and 19, were evaluated by ultrasonic C-scanning and judged to have good quality. Flexural specimens, taken from panel No.19, were tested (Table 8) at RT and 177° C (350° F). After this, the panels were placed into a humidity chamber where they were exposed to 82.2° C (180° F) and 98% relative humidity for a period of 30 days. The panels were removed from the humidity chamber every 5 days and weighed.

Percent moisture pick-up was calculated and plotted; daily measurements were made after the 25th day. The data indicates that full saturation was reached in 26 days. Figure 18 is a plot of the percent moisture gained in panel Nos.18 and 19 over the 30-day exposure period.

Panel Nos. 18 and 19 were removed from the humidity chamber and sealed in a plastic bag; 10 flexural specimens were machined from panel No. 19, and the remaining portion was sealed in a plastic bag and placed in a refrigerator to assure the moisture was retained.

Of the flexural specimens taken from panel No.19, five were tested at RT per FTMS406, Method 1031. The results of these tests are shown in Table 8. The remaining portion of panel No.19 was dried for 3 days at 121° C (250° F), and then was cut into flexural specimens and tested at RT and 177° C (350° F). The wet-test results are compared with the dry-test results to determine if moisture had reduced the composite properties. Table 8 is a tabulation of those test results.

Thermal cycle testing of 1000 cycles was conducted at the GE Re-Entry Systems Division in Philadelphia. The graphite/PMR15 panel, which had been fully saturated with moisture, was exposed to conditions simulating the rapid-temperature-rise experienced by the engine during acceleration to takeoff power. The rapidly heating air was provided by a gas arc facility. The temperature seen by the panel was measured by surface and back face thermocouples and monitored by temperature-sensitive paints. The airstream was stabilized at 538° C (1000° F) prior to insertion of the test panel. The panel was somewhat shielded, due to the 10° angle-of-attack between the panel and the airstream which created an insulating bow wave. The panel was left in the airstream until the front face surface temperature reached 246° C (475° F). This temperature was verified by both the thermocouples and the temperature-sensitive paint. When the front face reached 246° C (475° F), the panel was removed from the airstream and force-cooled to 82.2° C (180° F), and then, the cycle was repeated.

Table 8. Laminate Flexural Strength and Modulus Comparison, Before and After Exposure to Moisture.

PANEL #	EXPOSURE	CONDITION OF SPECIMEN	TEST TEMPERATURE ^{o}F (^{o}C)	SPECIMEN NUMBER	FLEXURAL PROPERTIES STRENGTH Psi	FLEXURAL PROPERTIES MODULUS E X 10^{6} Psi
19	None	Dry	$73^{o}F$ ($23^{o}C$)	1	129,890	10.5
				2	117,140	10.7
				3	115,290	10.4
				4	122,590	10.4
				5	136,320	10.2
				Avg.	124,246	10.4
19	$180^{o}F$ & 98% RH for 30 days	Fully Saturated 1.3% Moisture		1	132,580	9.2
				2	133,570	9.4
				3	124,860	9.0
				4	134,790	9.4
				5	134,630	9.4
				Avg.	132,086	9.28
19	None	Dry	$350^{o}F$ (176^{o})	1	129,630	9.4
				2	122,930	9.7
				3	116,920	9.6
				4	134,000	9.5
				5	118,750	9.2
				Avg.	124,446	9.48
19	$180^{o}F$ & 98% RH for 30 days	Fully Saturated (1.3% Moisture 3 days @ $250^{o}F$ to 0% moisture level		1	106,160	8.4
				2	109,280	8.6
				3	105,190	8.3
				4	103,980	8.0
				5	88,300	8.1
				Avg.	102,582	8.28

After the thermal cycle testing, panel No. 18 was cleaned of surface contaminants and reevaluated by ultrasonic C-scanning; the C-scanning indicates a panel of good quality. Several areas indicate a higher attenuation coefficient than the C-scan performed on the panel before thermal cycling. These areas generally coincide with the areas where the surface contaminants were most difficult to remove. The humidity exposure and flexural testing performed on panel No.19 was then repeated on panel No.18.

Test results were compared with data obtained from panel No.19 to determine whether the thermal cycling caused any significant reduction in properties. Table 9 presents data from these flexural specimens. Strength and modulus retention is compared in Figure 19. Due to the change in modulus, the material left after preparing the flexural specimens from panel No. 18 was prepared for compressive testing. Table 10 lists the results. Comparing these results with the compressive test data of unexposed material showed that the data from the thermally cycled panel fell within the test scatter of that data; therefore, no degradation in compressive strength or modulus due to thermal cycling could be detected from the data generated.

4.5 Subcomponent Testing

An extensive subcomponent test program was conducted to evaluate the duct design and to verify that it satisfied all of the F404-GE-400 engine technical requirements.

4.5.1 Buckling Characteristics Test

A 76.2-cm (30-in.) long by 50.8-cm (20-in.) diameter composite cylinder was fabricated with a 50.8-cm (20-in.) long 4-ply test section as shown in Figure 20. The duct was attached to end plate fixturing for loading the subcomponent in buckling. Twenty strain gauges were installed, as shown in Figure 21. The original test plan was to load the buckling test article until the onset of buckling (without failure) under the following four loading conditions:

- Axial compression
- Axial compression plus internal pressure
- Bending
- Bending plus internal pressure.

For the initial stages of loading, a strain limitation of 0.001150 was imposed; this corresponds with a compressive stress of 55 MPa (8 ksi) which was the average buckling stress allowable predicted for the test article (using several predicting equations).

The first three loading conditions were run up to the strain limitations without detecting the onset of buckling. In lieu of conducting the fourth test condition, a rerun of the first test condition was set up to go beyond the initial strain limitation. The test article failed in buckling at 147-KN (33,000-lb) axial compressive load which represented an average strain in the cylinder wall of 0.001443 or 69.6 MPa (10,100 psi). The actual strains being recorded by the strain gauges are shown in Figures 22 through 27; as can be seen from these data, the cylinder

Table 9. Laminate Flexural Strength and Modulus After Thermal Cycling and Exposure to Moisture.

PANEL#	EXPOSURE	SPECIMEN	TEST TEMP. °F (°C)	SPECIMEN NUMBER	FLEXURAL PROPERTIES STRENGTH PSI	FLEXURAL PROPERTIES MODULUS E X 10^6 PSI
18	180°F & 98% RH For 30 Days	Fully Saturated	73°F (23°C)	1	115,860	6.7
				2	113,130	6.8
				3	115,600	6.6
				4	112,620	6.8
				5	116,630	6.6
				Avg.	114,768	6.7
18	180°F & 98% RH For 30 Days		350°F	1	94,950	5.5
				2	92,240	5.3
				3	92,130	5.4
				4	93,920	5.3
				5	94,340	5.3
				Avg.	93,516	5.36

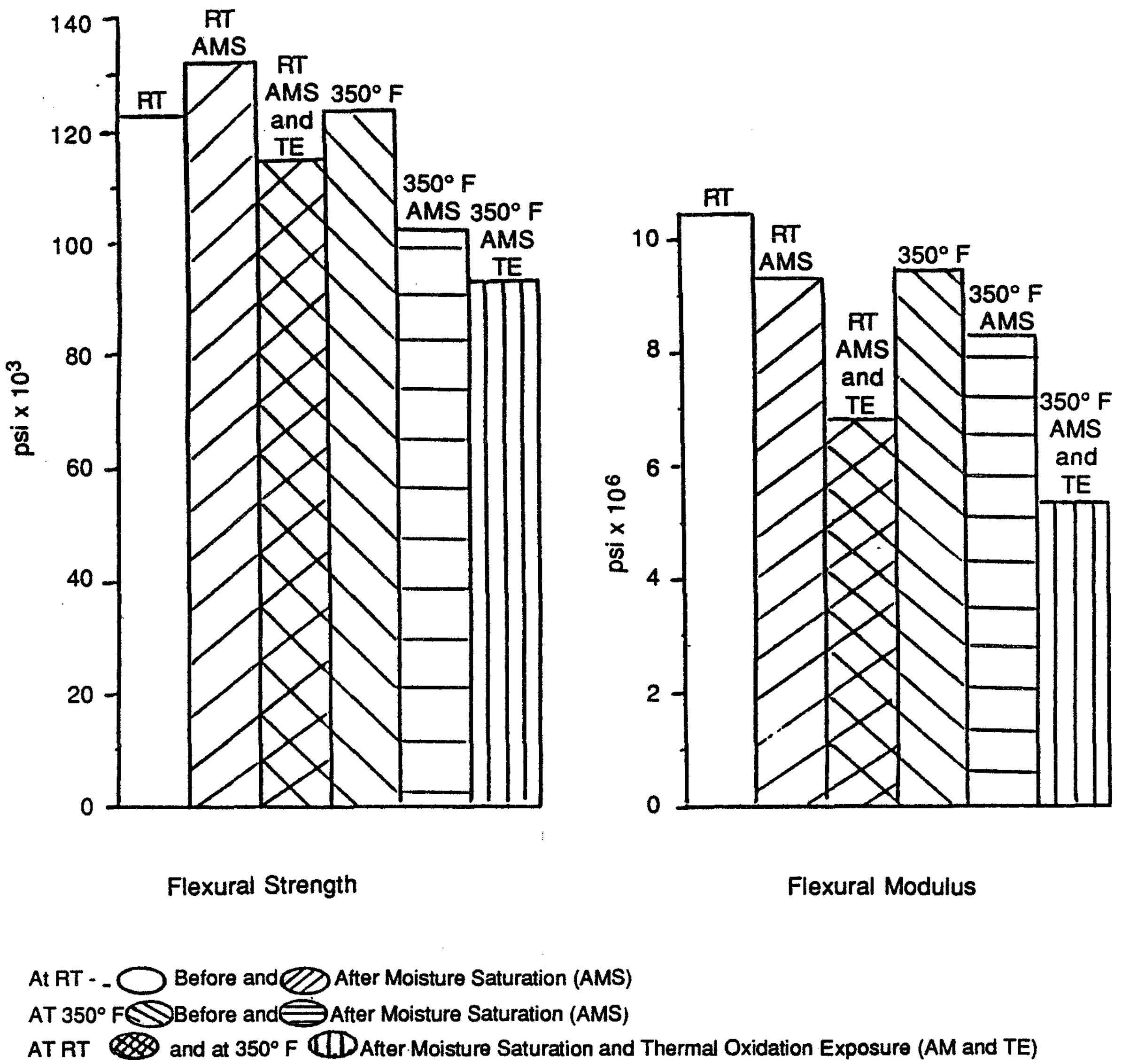


Figure 19. Flexural Strength and Modulus (0°, -45°, 0°).

Table 10. Compressive Strength and Modulus of Panel No. 18 After 1,000 Thermal Cycles.

TEST SPECIFICATION	LOT NO.	PANEL NO.	SPECIMEN DIMENSIONS	TEST TEMP.	COMPRESSIVE STRENGTH PSI	COMPRESSIVE MODULUS MSI
FTMS 406 Method 1021	USP 9456	18	0.052 x 0.497 x 3	73°F	47,670	10.9
General Dynamics FPS-1028 (A)	USP 9456	18	0.052 x 0.500 x 1-1/4	73°F	44,460	-
			0.053 x 0.502 x 1-1/4		45,850	-
			0.053 x 0.501 x 1-1/4		43,760	-
			0.053 x 0.502 x 1-1/4		45,850	-
					44,980 Avg.	
FTMS 406 Method 1021	USP 9456	18	0.053 x 0.499 x 3	350°F	37,510	6.34
General Dynamics FPS-1028 (A)	USP 9456	18	0.052 x 0.501 x 1-1/4	350°F	43,370	-
			0.052 x 0.501 x 1-1/4		37,920	-
			0.053 x 0.501 x 1-1/4		33,970	-
			0.052 x 0.502 x 1-1/4		39,760	-
					38,760 Avg.	

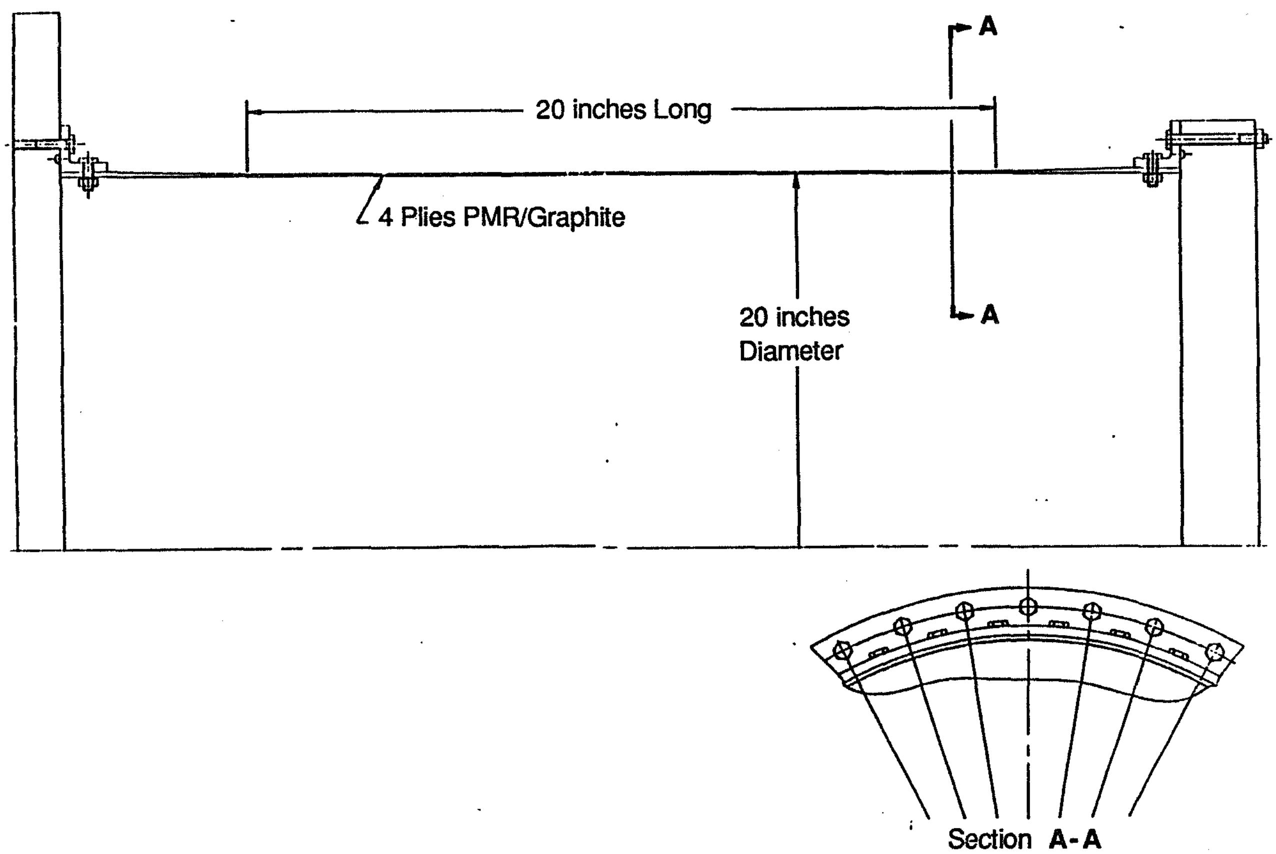


Figure 20. PMR/Graphite Buckling Test Article.

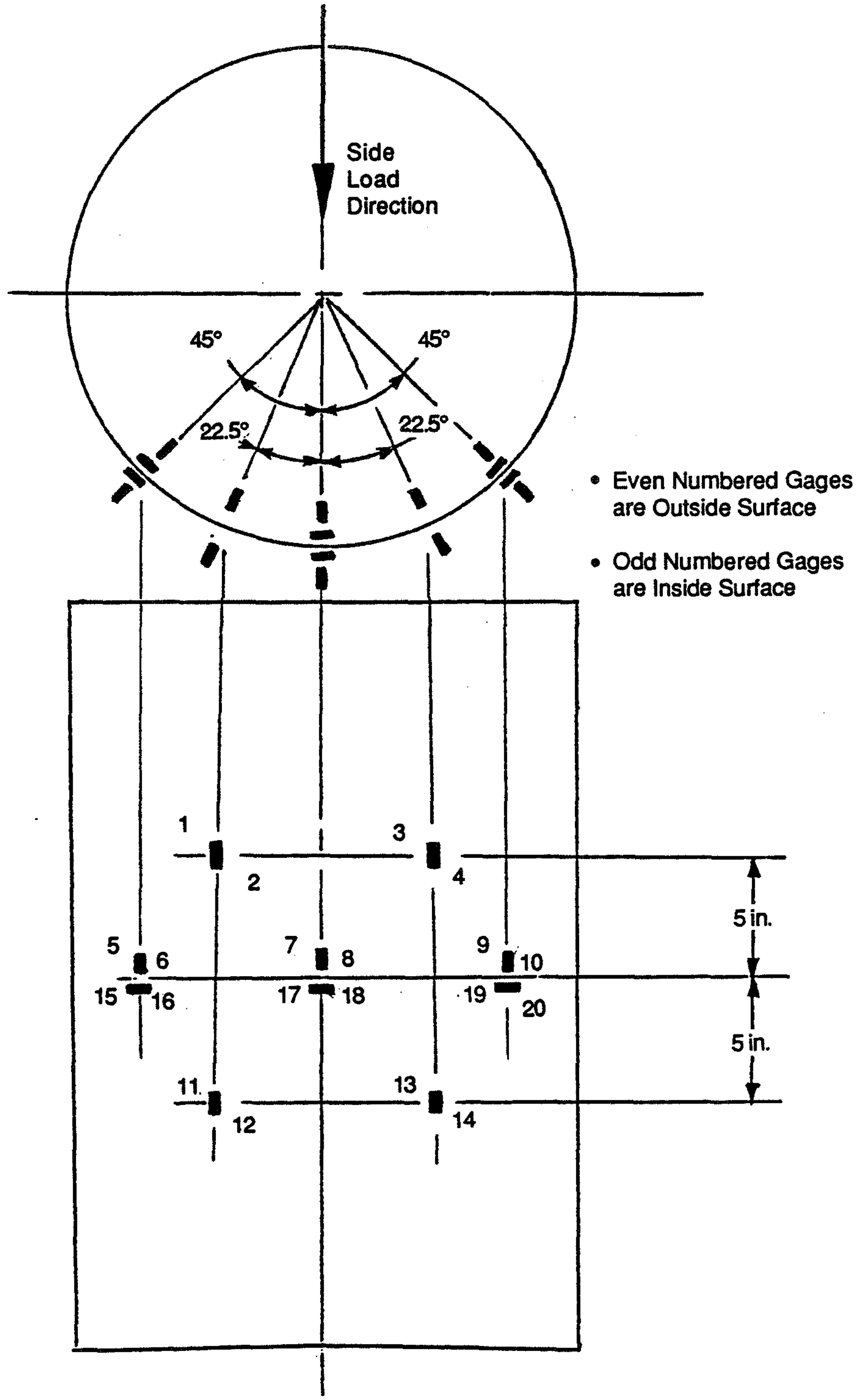


Figure 21. Buckling Test Cylinder Strain-Gauge Sketch.

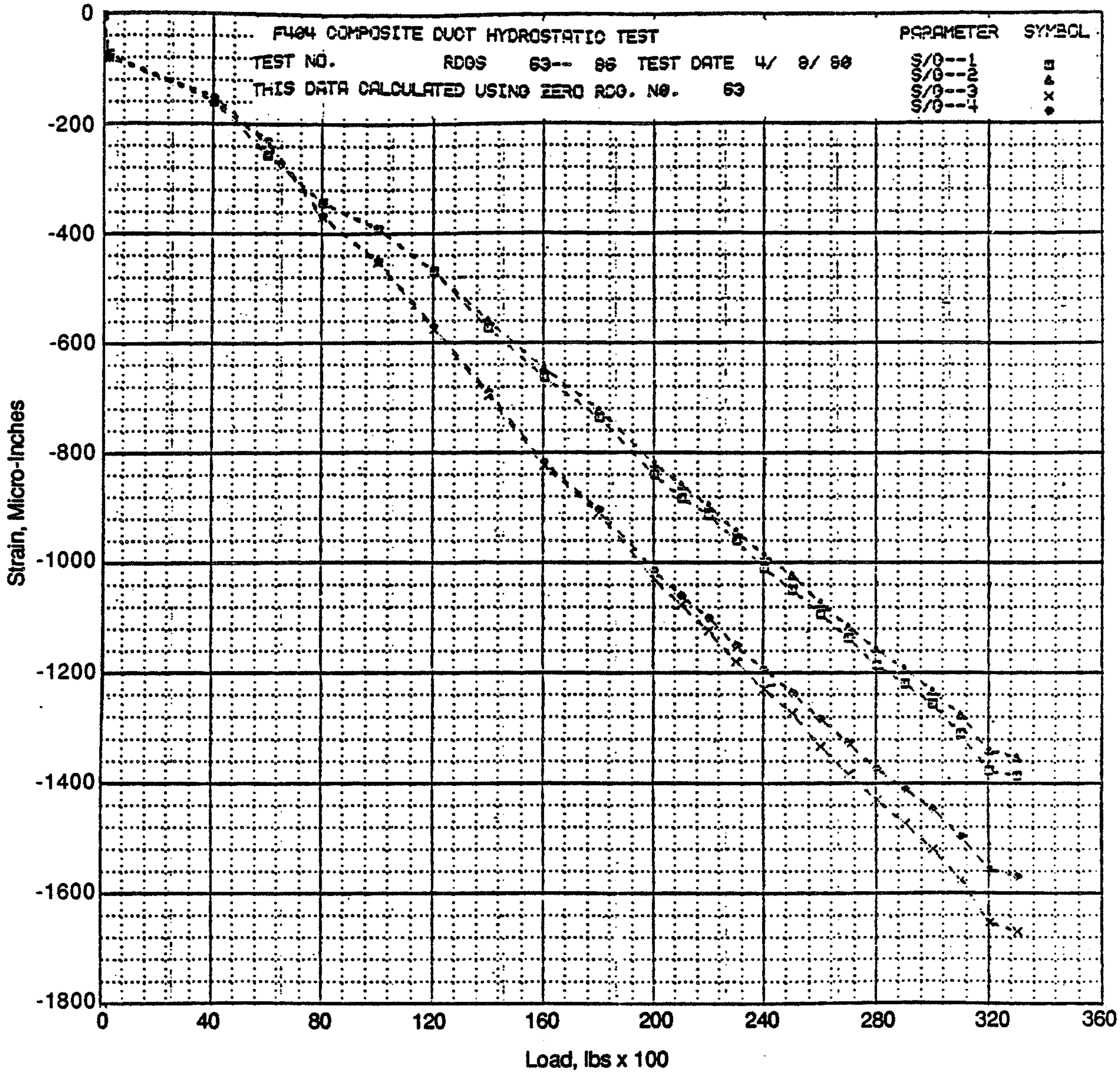


Figure 22. F404 Composite Duct Hydrostatic Test.

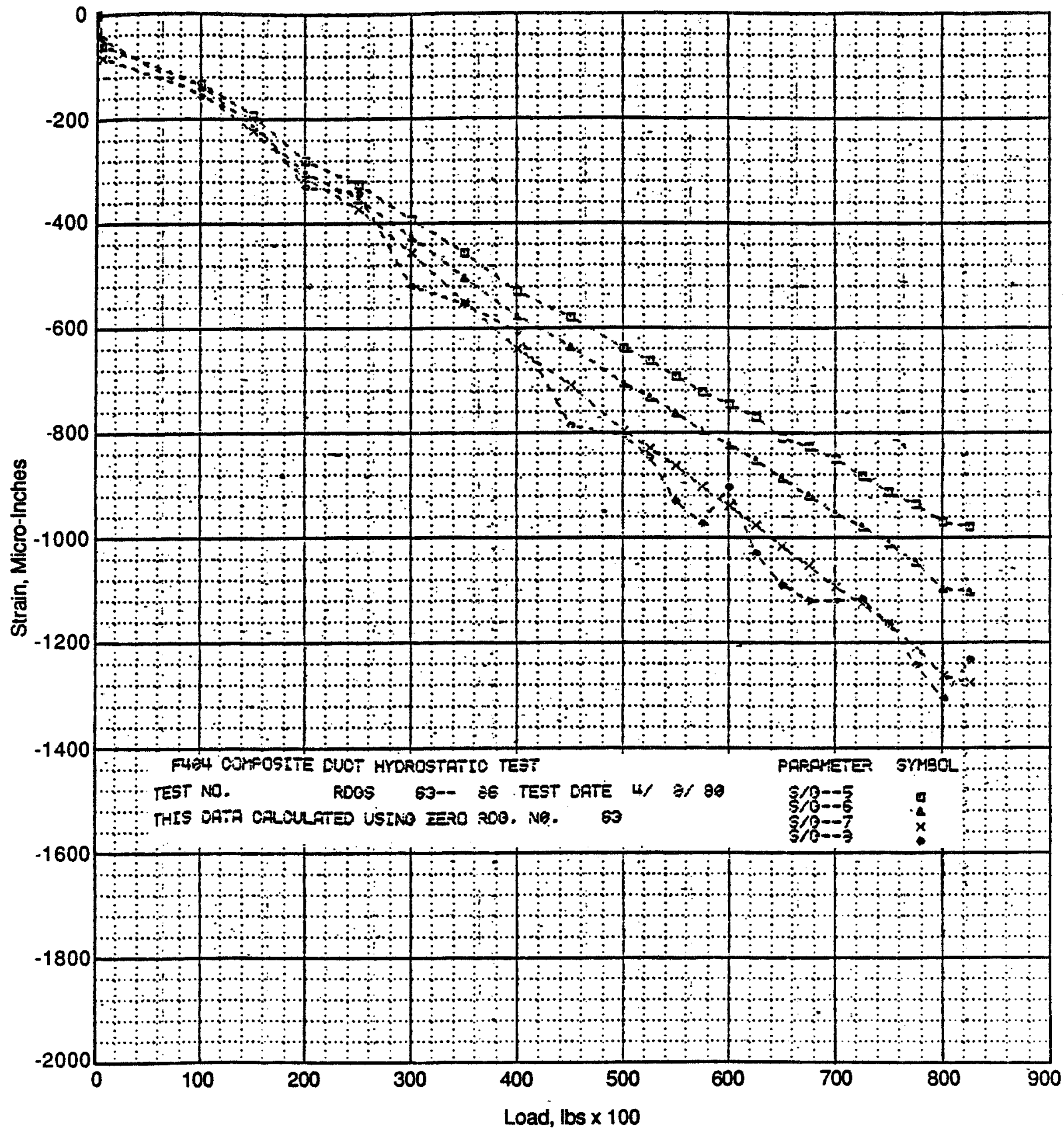


Figure 23. Composite Duct (F404) Hydrostatic Test.

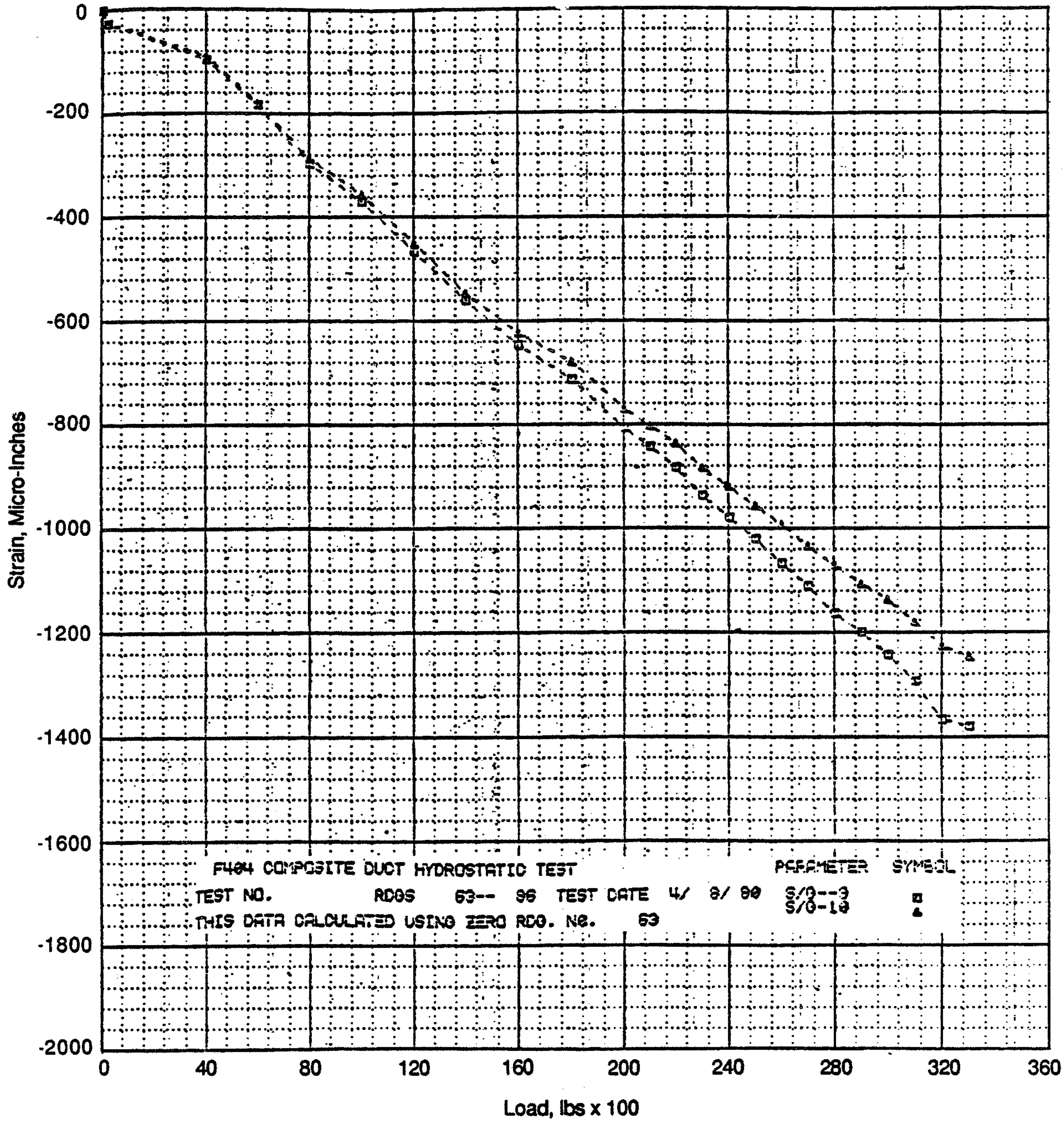


Figure 24. Hydrostatic Test Results of the F404 Composite Duct.

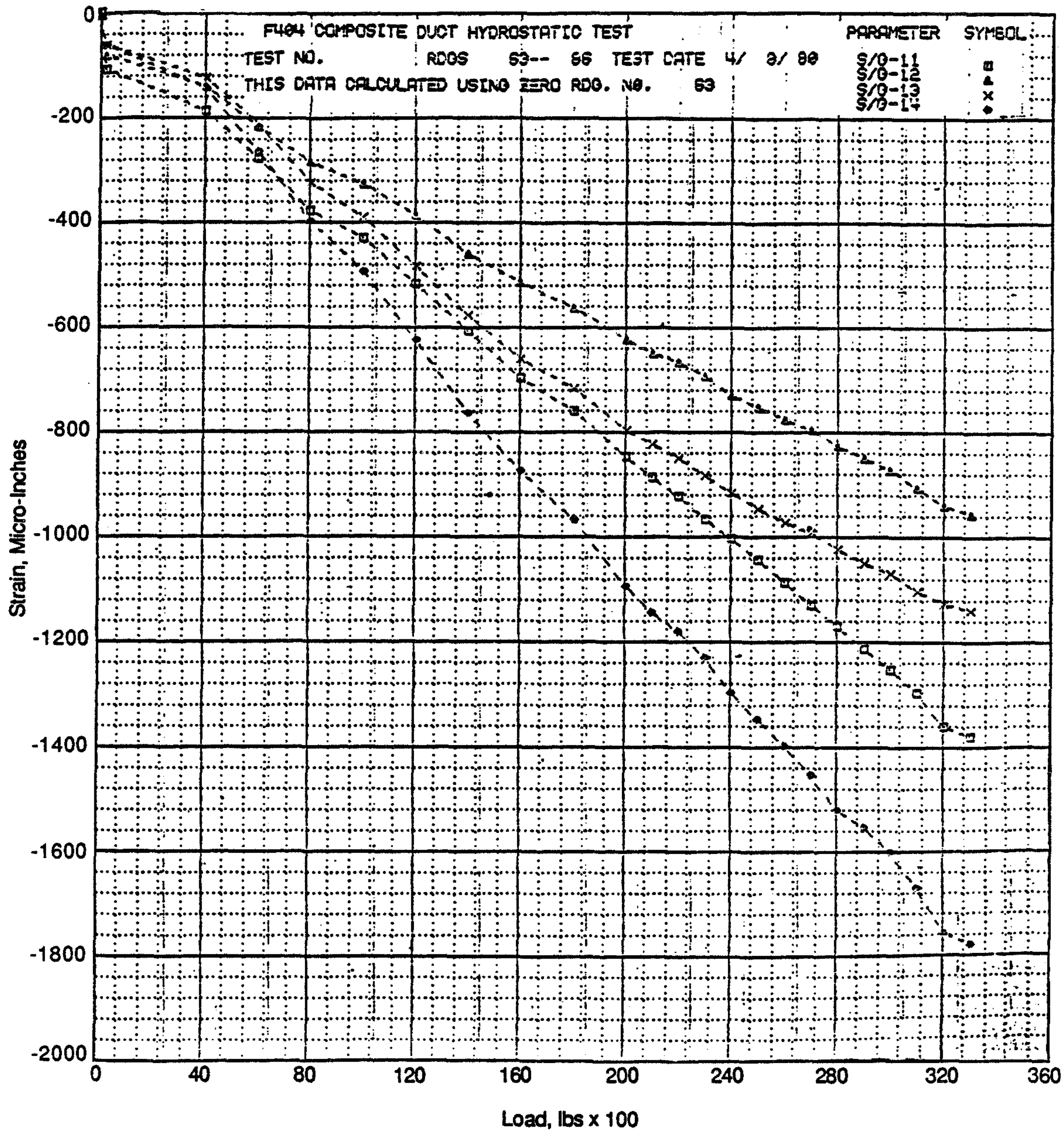


Figure 25. F404 Composite Duct Hydrostatic Test Results.

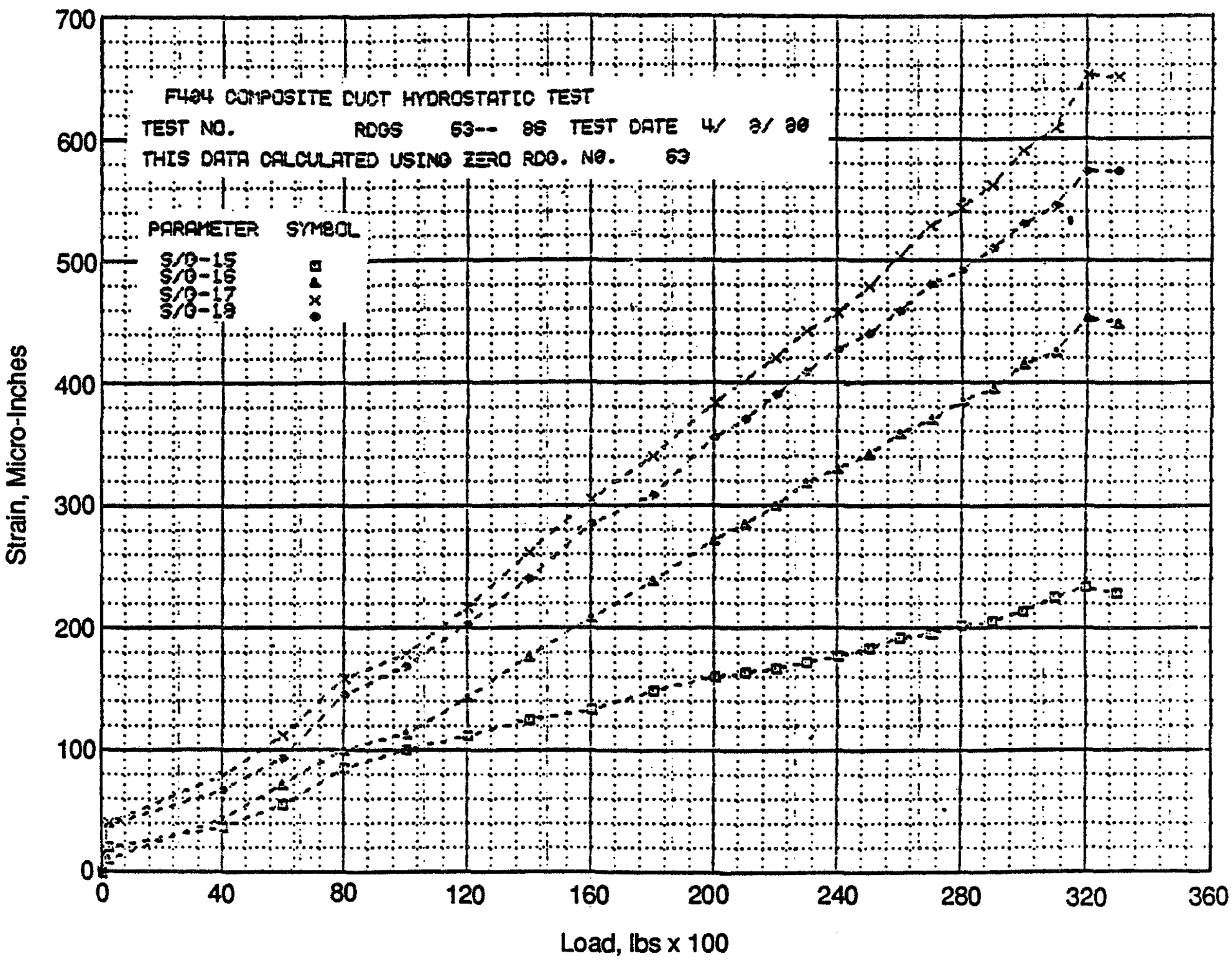


Figure 26. Hydrostatic Test Results (F404 Composite Duct).

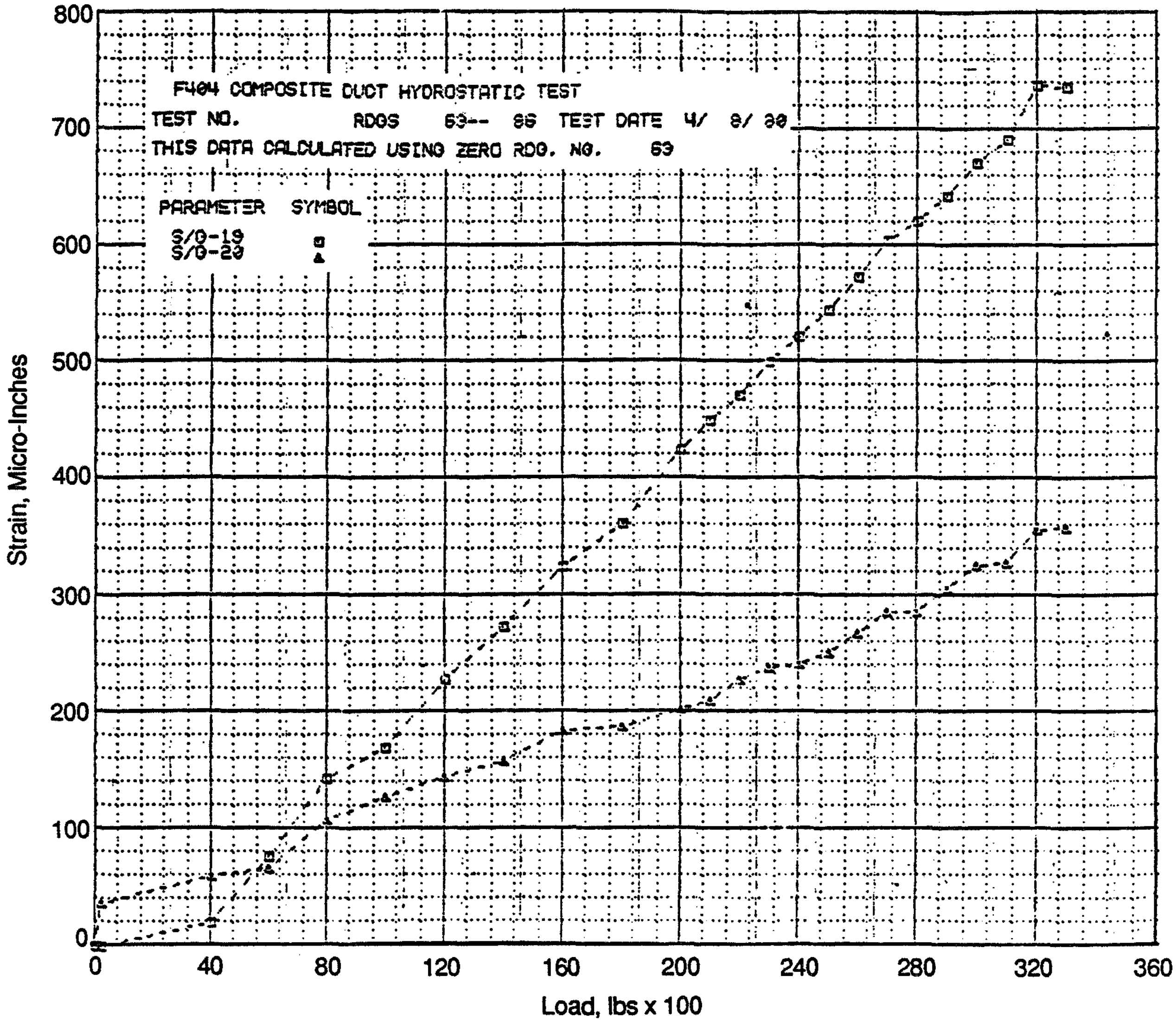


Figure 27. F404 Composite Duct Hydrostatic Test.

was not straining uniformly. The maximum strain recorded was 0.001781, indicating a stress level of 86 MPa (12,470 psi).

Utilizing the same analytical approach as was used for the duct preliminary design, the test cylinder was predicted to buckle at an average wall stress of 63.5 MPa (9220 psi). Testing, therefore, showed good agreement with the analytical procedure. The analysis was just slightly conservative, the average failing load being only 10% greater than that predicted. Some of the other analytical methods previously considered proved to be excessively conservative and will no longer be used.

4.5.2 Actuator Attachment Test

The composite duct supports two high pressure compressor variable geometry actuators, at 1:30 and 7:30 o'clock, at the forward end of the duct (see Figure 28 for specimen definition). The actuator can exert up to 2670 N (600 lb) force. This force was cycled 101,000 times without damage to the specimen. At partial load, 101,000 cycles represent one full 4000-hour actuating system life.

4.5.3 Flange Testing

Subcomponent tests were conducted on the initial riveted titanium-end flange specimen illustrated in Figure 29, and on the initial double doubler split-line flange specimen depicted in Figure 30. Two each of two subcomponents representing the axial split-line joint and the forward/aft titanium flange to graphite duct circumferential attachment were fabricated and tested. One each of the two types of specimens were tested statically to failure. The axial split-line flange specimen failed at 6059 N/cm (3460 lb/in.) compared to the maximum design condition of 1891 N/cm (1080 lb/in.) limit load. The subcomponent representing the riveted joint between the composite shell and titanium-end flanges failed at 3975 N/cm (2270 lb/in.), compared to a maximum design requirement of 1716 N/cm (980 lb/in). The other specimen of each type was fatigue-tested. The bolted, axial, split-line joint specimen was cycled 10,000 times to 1891 N/cm (1080 lb/in.), which represents the load due to the maximum operating delta pressure of 496 KPa (72 psi); there was no apparent damage to the test specimen. The test specimen representing the riveted-end attachment was cycled 10,000 times to a load of 1716 N/cm (980 lb/in.), which is equivalent to the load caused by the maximum maneuver condition; again, no damage was noted.

Subcomponent tests also were conducted on the composite flanges developed under Task XI. Straight segments representing the duct forward flange, aft flange, and split-line flange were tensile-tensile fatigue tested at room temperature and at 177° C (350° F), see Figure 31. The maximum flange loading was cyclically applied to the flange specimens for 10,000 cycles. These specimens were then tensile tested to failure, along with flange specimens which had not been load cycled. The flange failure loads all exceeded 2.5 times the maximum operating load, with and without load cycling. The load cycled specimens, in some cases, failed at loads higher than the non-cycled specimens; however, the differences are not significant. The conclusions of this

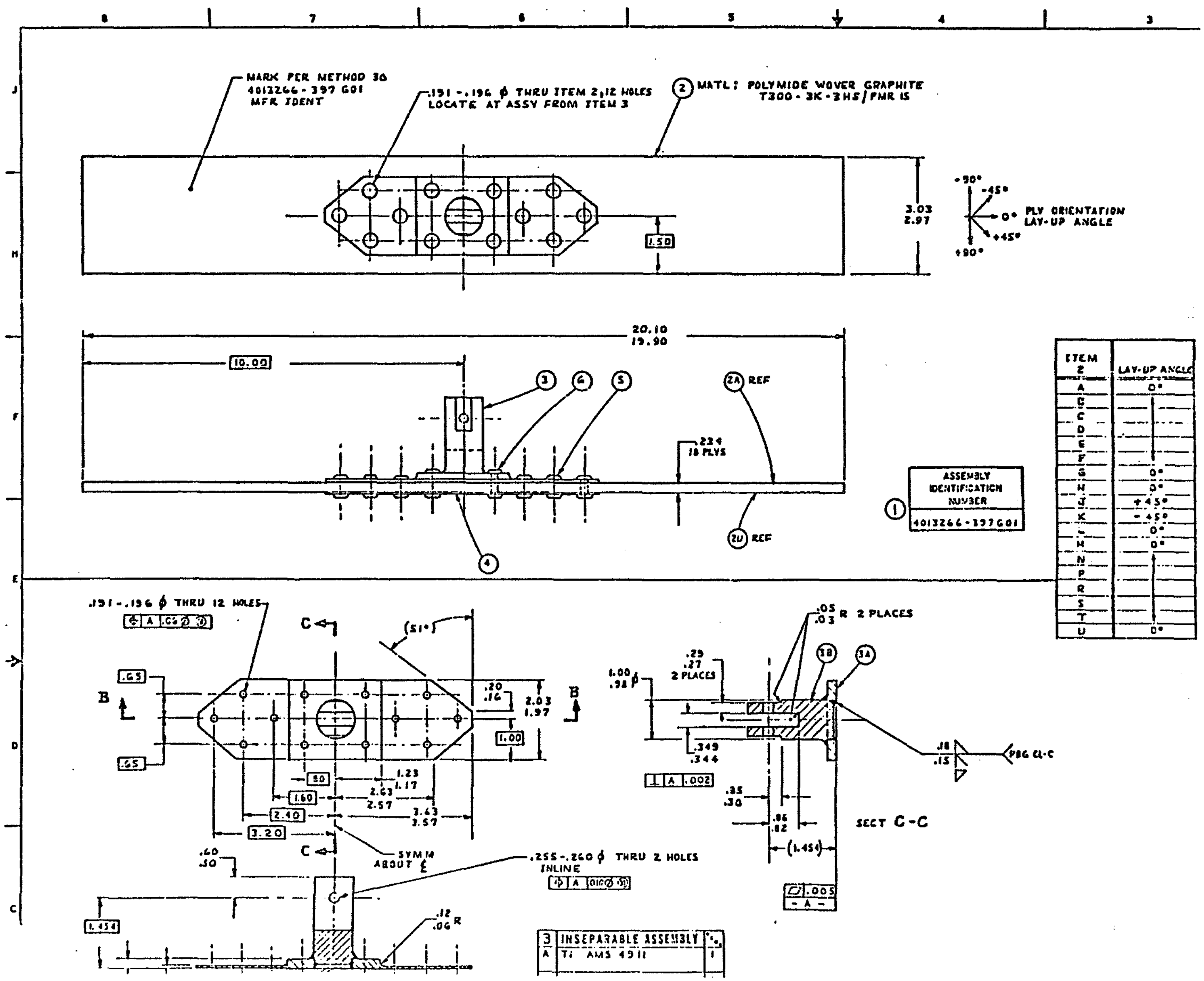
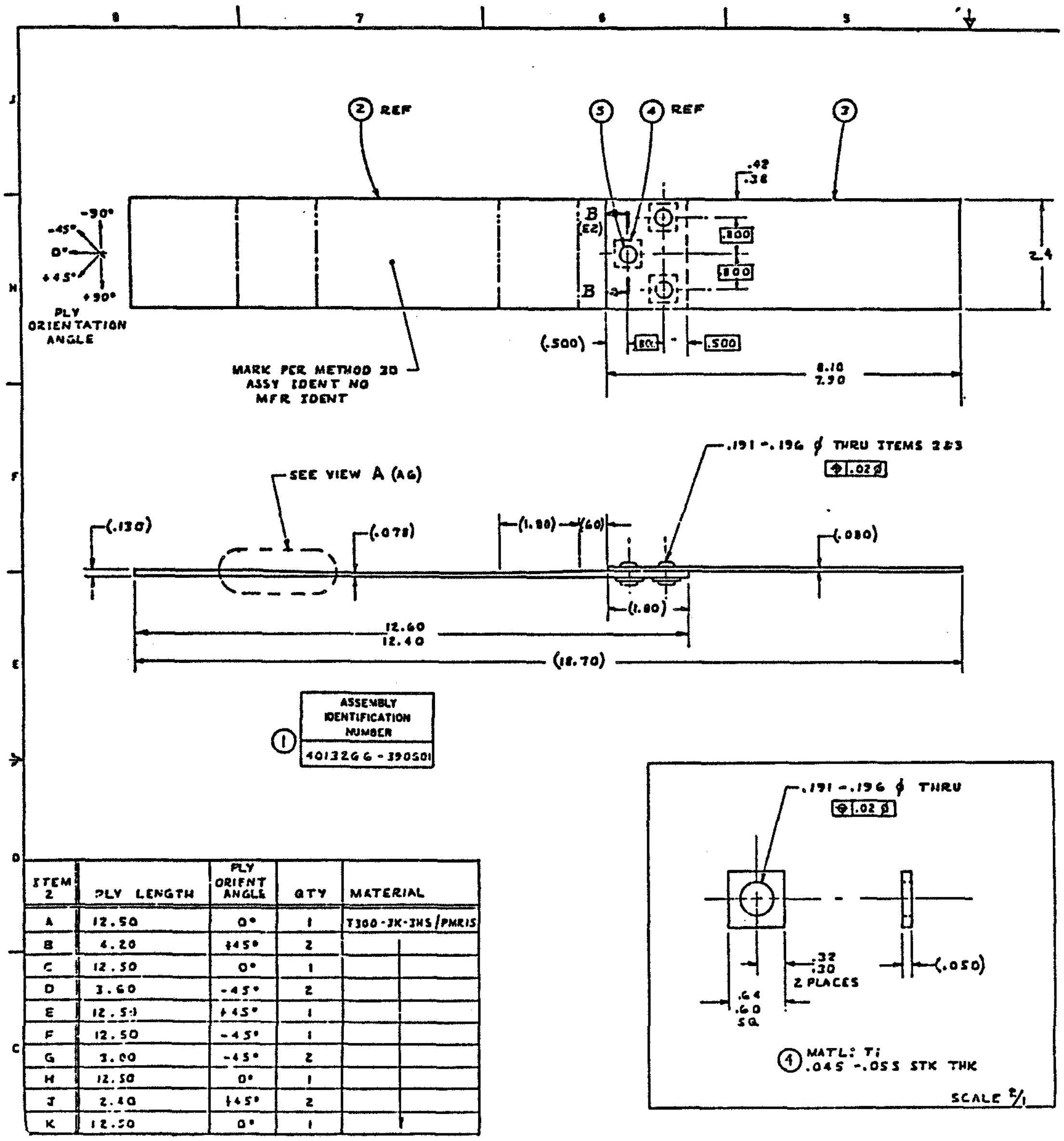
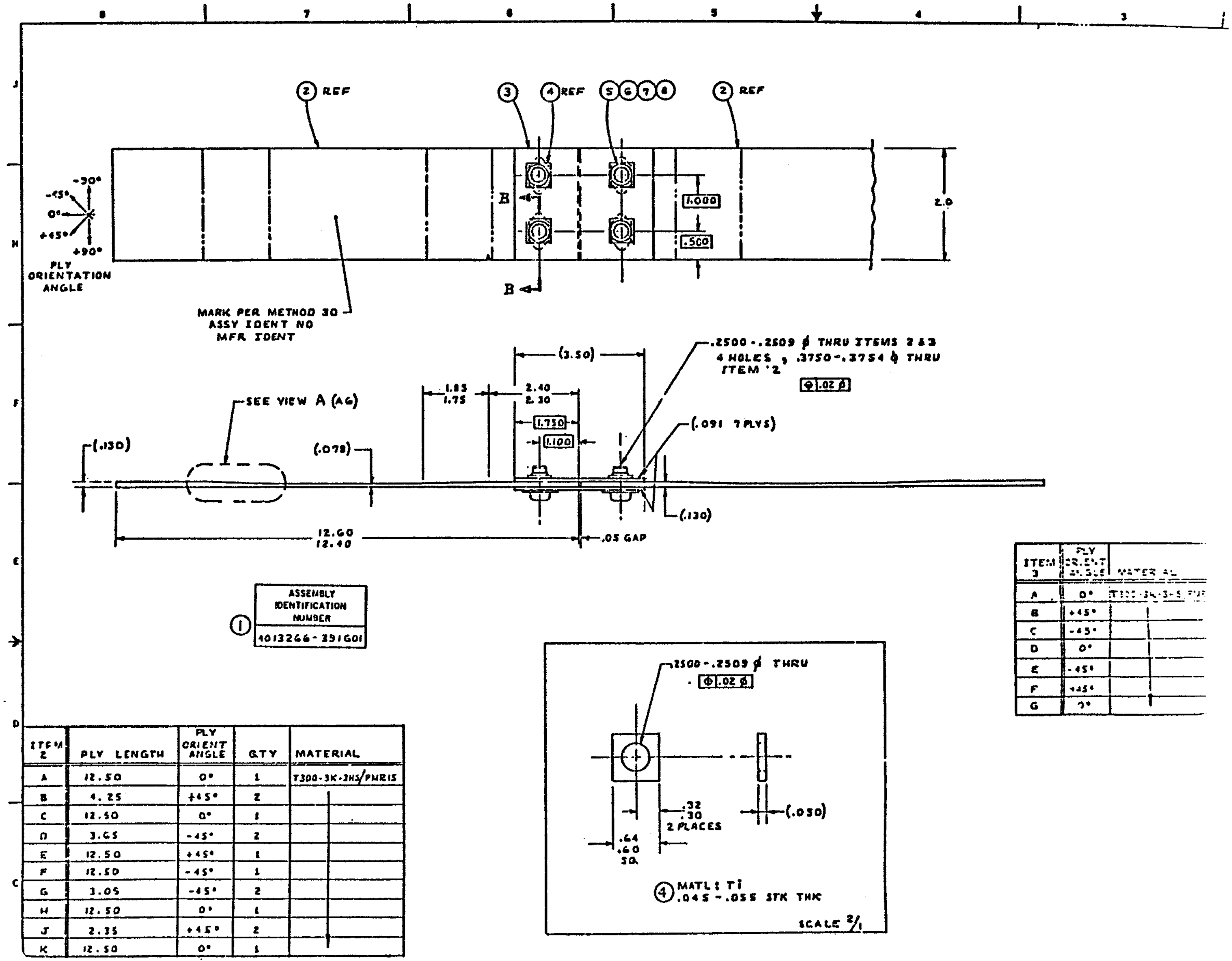


Figure 28. High Pressure Variable Geometry Actuator Subcomponent Specimen.



ITEM 2	PLY LENGTH	PLY ORIENT ANGLE	QTY	MATERIAL
A	12.50	0°	1	T300-3K-3HS/PMR15
B	4.20	±45°	2	
C	12.50	0°	1	
D	3.60	-45°	2	
E	12.50	+45°	1	
F	12.50	-45°	1	
G	3.00	-45°	2	
H	12.50	0°	1	
J	2.40	±45°	2	
K	12.50	0°	1	

Figure 29. Initial Riveted Titanium-End Flange Subcomponent Specimen.



ITEM 2	PLY LENGTH	PLY ORIENT ANGLE	QTY	MATERIAL
A	12.50	0°	1	T300-3K-3HS/PMR15
B	4.25	+45°	2	
C	12.50	0°	1	
D	3.65	-45°	2	
E	12.50	+45°	1	
F	12.50	-45°	1	
G	3.05	-45°	2	
H	12.50	0°	1	
J	2.35	+45°	2	
K	12.50	0°	1	

ITEM 3	PLY ORIENT ANGLE	MATERIAL
A	0°	T300-3K-3-5 [illegible]
B	+45°	
C	-45°	
D	0°	
E	-45°	
F	+45°	
G	0°	

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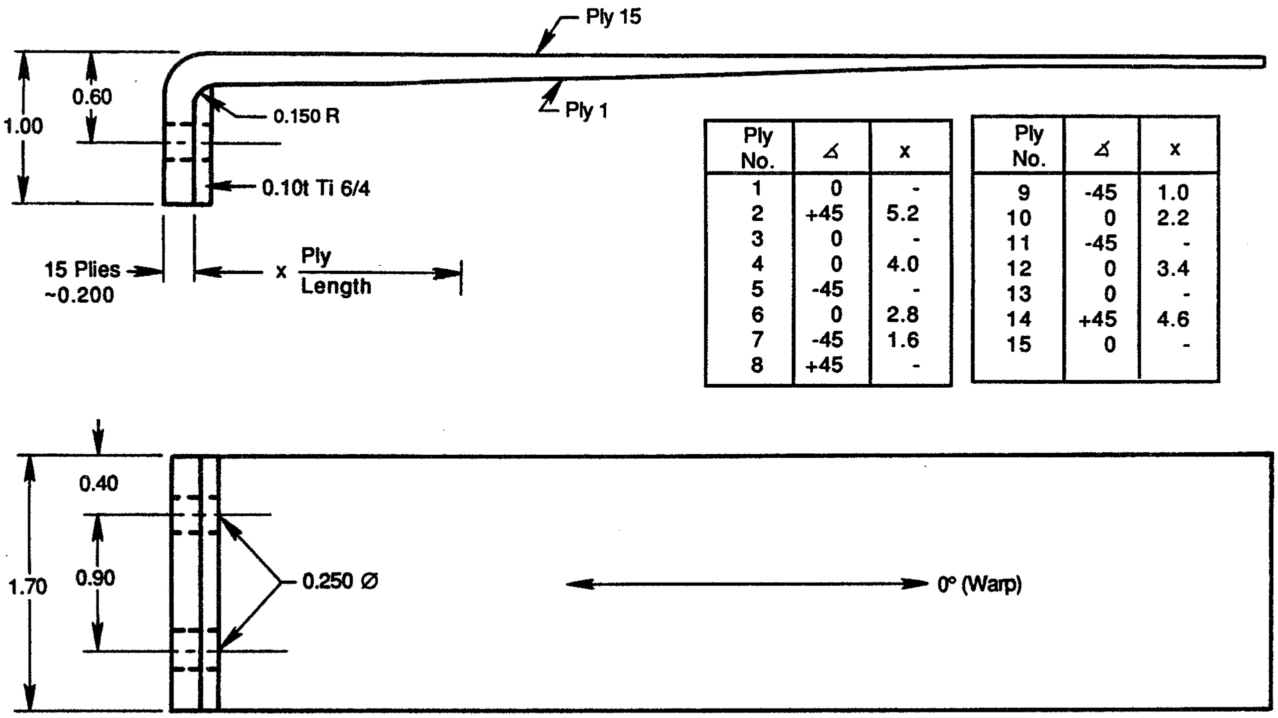
Figure 30. Initial Double-Doubler Split-Line Subcomponent Specimen.



Ply No.	∡	x
1	0	-
2	+45	5.2
3	0	-
4	0	4.0
5	-45	-
6	0	2.8
7	-45	1.6
8	+45	-

Ply No.	∡	x
9	-45	1.0
10	0	2.2
11	-45	-
12	0	3.4
13	0	-
14	+45	4.6
15	0	-

Figure 31. Straight-Flange Specimen.

testing were that the flanges have a design load margin of 1.5 and that fatigue loading of the composite flanges at their maximum operating load did not affect their ultimate load capability. Similar tests were run on curved flange specimens representing the duct forward flange (Figure 32). The forward duct flange corner joint, where the split-line flanges meet, was tested using a flat laminated specimen as shown in Figure 33. The failure load of this specimen was over three times the maximum operating load. These results are listed in Table 11 for the five flanged specimen configurations.

These subcomponent flange test results indicated that the integral composite flanges in the final duct product would be structurally adequate. The final proof of the composite flange design was a full-scale pressure test of a composite flanged barrel having both composite split-line flanges and end flanges. This test setup is demonstrated in Figure 34. The split-line and end flanges were tested up to 1.5 times the maximum operating pressure without rupture or any other damage.

4.6 Duct Fabrication

4.6.1 Duct Fabrication Process

The principle concept of molding the shell is to vacuum-bag-autoclave mold on the outside diameter of a cylindrical steel mandrel or mold tool (Figure 35). The molded cylindrical part

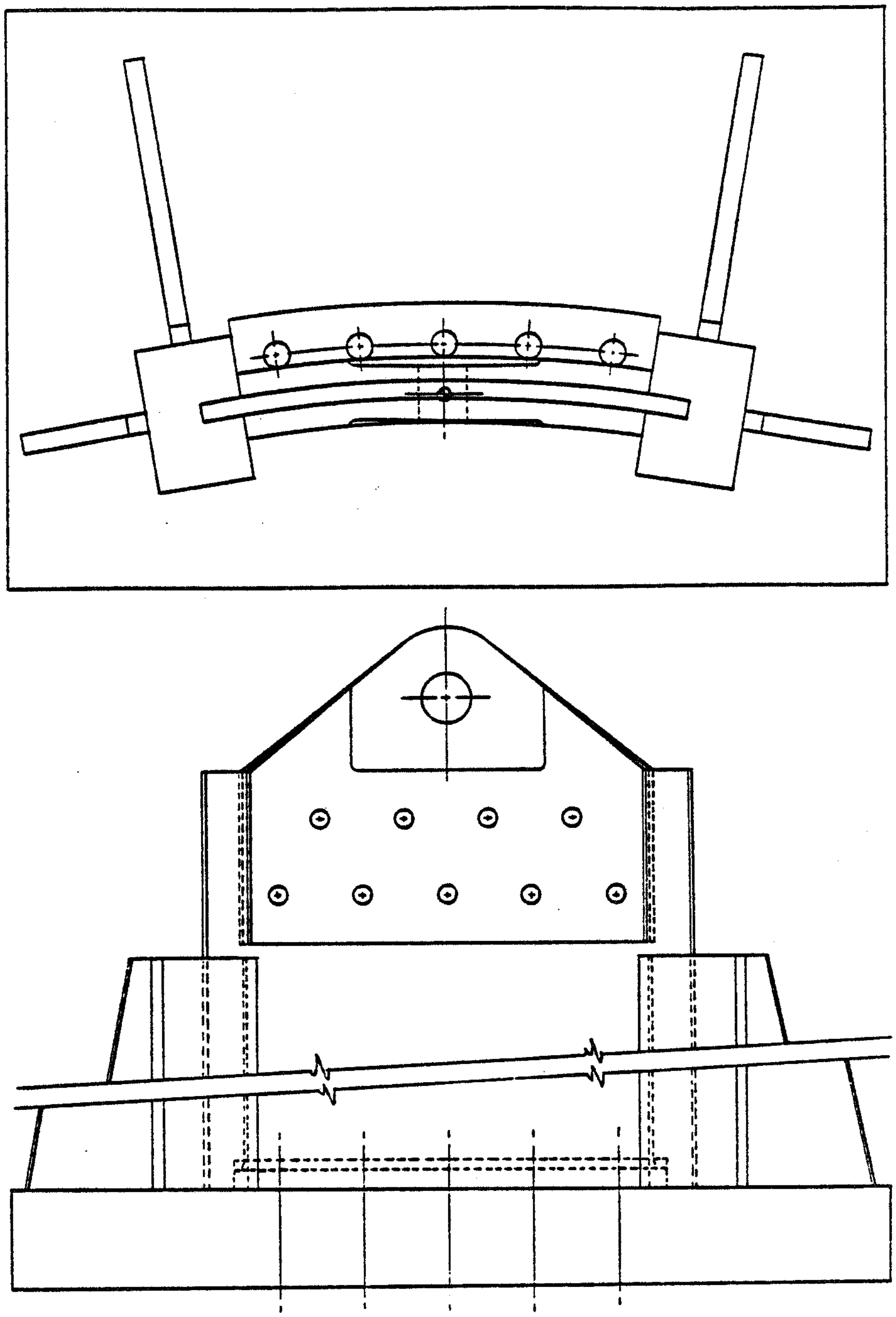


Figure 32. Curved-Flange Specimen Test Fixture.

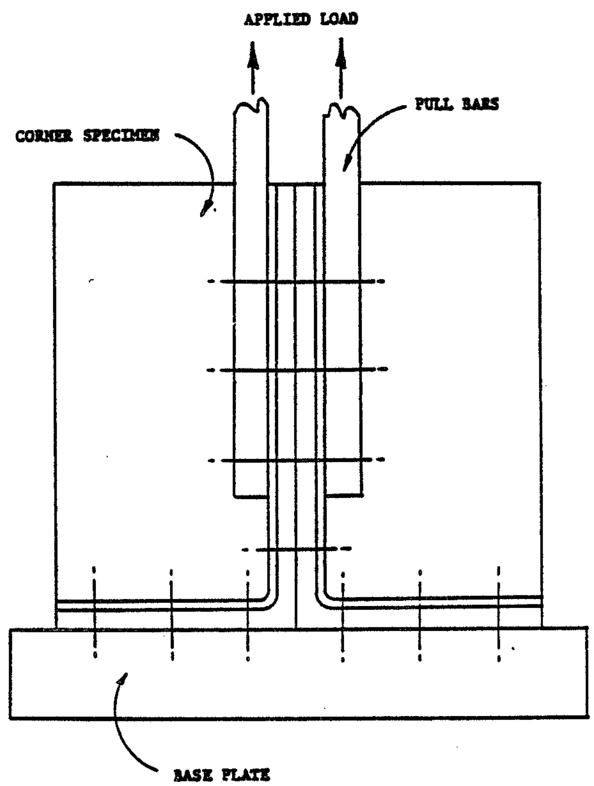


Figure 33. Composite Corner-Flange Spectrum.

Table 11. Subcomponent Test Results.

Configuration	Failure Load (lb/in) Room Temperature	Failure Load (lb/in) 350°F	Fatigue Load (lb/in) (10,000 Cycles) Room Temperature	Fatigue Load (lb/in) (10,000 Cycles) 350°F
Aft Flange - Straight - Type A	2483	2662	-	-
	2955	2303		
	3070	2478	980	980
	2896	2517		
Forward Flange - Straight - Type B	3416	2459	-	-
	3469	2390		
	3057	2541	980	980
	3219	2546		
Split Line Flange - Type C	2785	2325	-	-
	2990	2385		
	3045	2855		
	2890	2960	1080	1080
Forward Flange - Curved - Type E	3200	2940	-	-
	3277	3055	980	980
	-2974	-2757	-	-
	-3330	-2617	-980	-980
Corner Flange - Type D	16141*	13938*	-	-

* Pounds

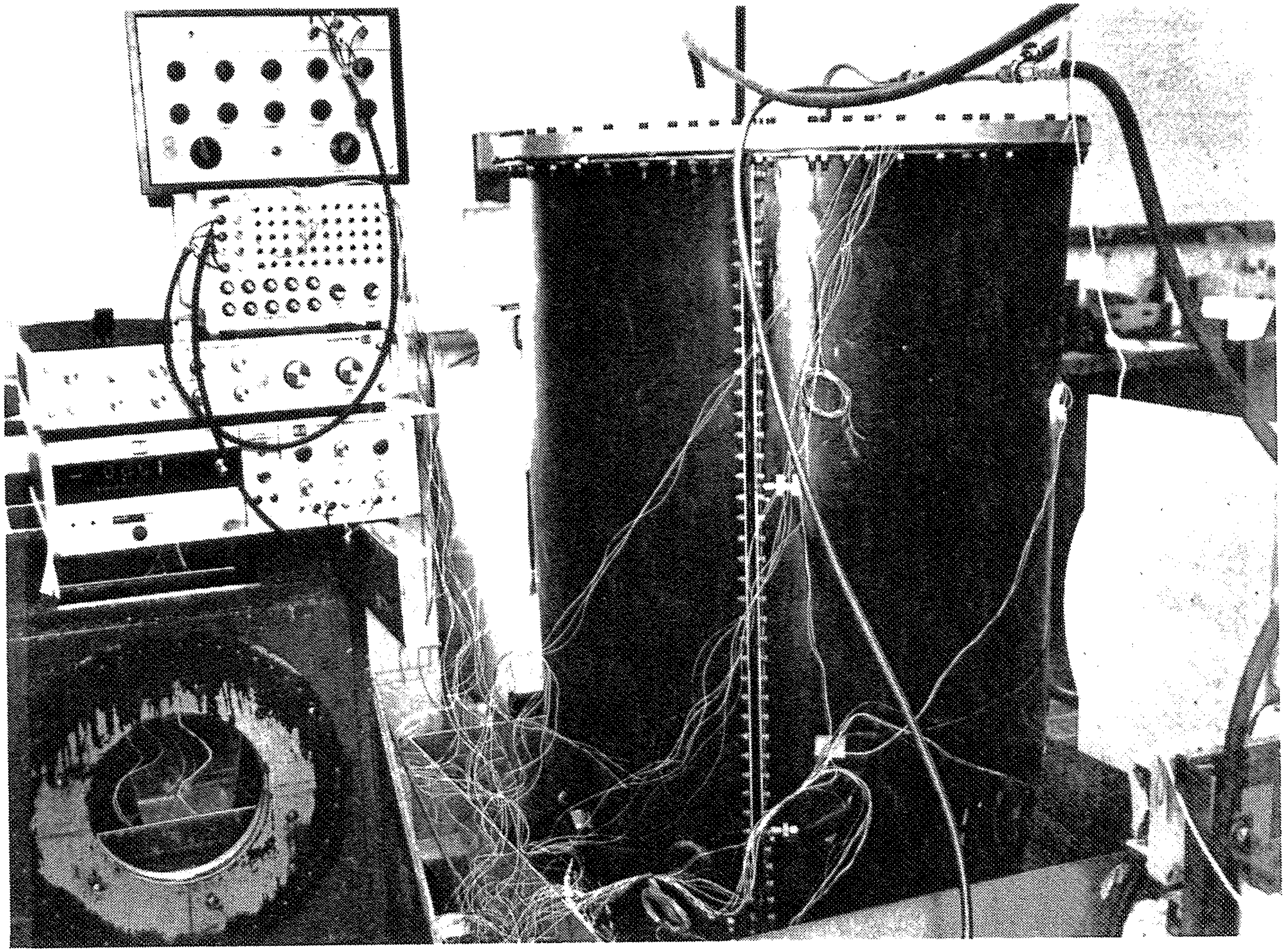


Figure 34. Full-Scale Composite-Flange Pressure Test.

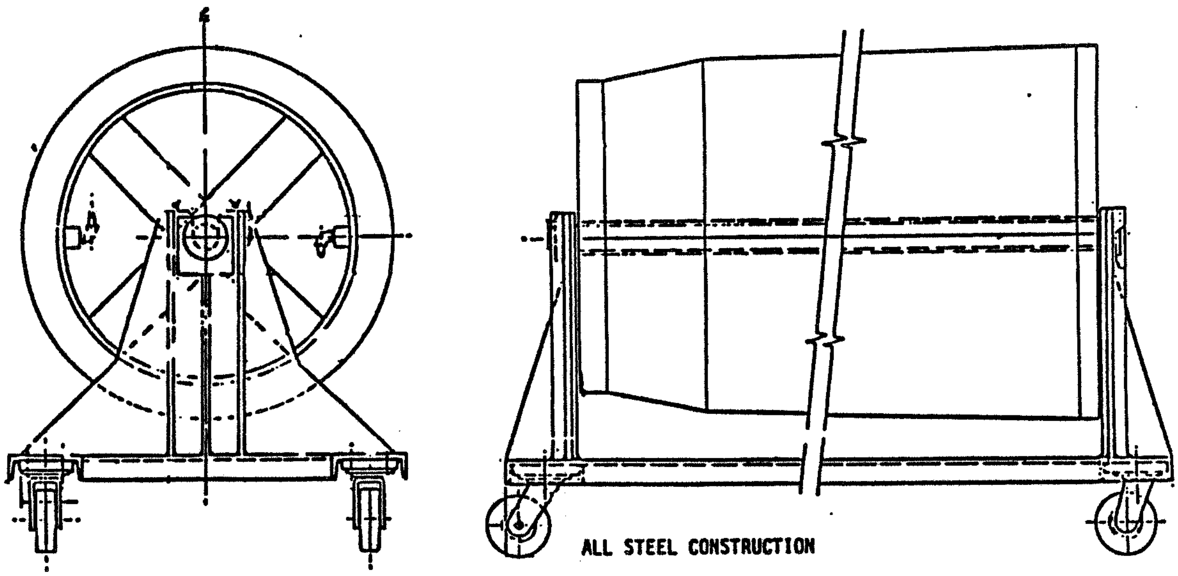


Figure 35. Autoclave Mold Tool for the F404 Composite Outer Duct.

will be cut into the upper and lower halves at a later time. This concept was selected as the simplest of the several concepts that were proposed; the advantages being as follows:

- Straightforward - lowest-cost mold tool
- Ease of laying up the graphite/PMR15 prepreg
- As-molded, smooth ID surface on the airflow side.

As-received, graphite fabric/PMR15 prepreg is nominally 0.457 to 0.559 mm (18 to 22 mils) thick; the final molded thickness of the prepreg is nominally 0.356 mm (14 mils). The process must include a debulking operation, or severe wrinkling of the prepreg may occur, especially when it is processed 7- to 11-plies thick in cylindrical form. The vacuum-bag-autoclave process applies the molding pressure to the prepreg and forces it to compact against the cylindrical tool. If the diameter of the uncured laminae is greater than the diameter of the finished part, the laminae will tend to wrinkle as the part is molded. This occurs even though the mold tool expands considerably during heat-up to 302° C (575° F).

The vacuum-bag-autoclave method of molding provided a satisfactory method of molding all of the test panels. This method, however, produces considerable "bleeding" or resin loss during an early phase of the portion of the process called "imidization." This bleeding is due to the very low resin viscosity of the melted monomers and the very light vacuum that is applied to hold the vacuum-bag system together in the high air velocity environment of the autoclave.

A more desirable approach is to achieve a "net resin" molding; this has been utilized in making the duct shell. This technique is somewhat akin to press molding, whereby the prepreg is imidized in an oven without vacuum pressure. Without bleed or resin loss, other than the volatiles lost during imidization, the entire resin content is available for molding. This procedure allows for a uniform, known resin content in the final part.

The duct-shell molding process is divided into three primary parts:

- Prepreg Lay-Up (on the mold tool)
- Oven-Imidization
- Vacuum-Bag-Autoclave Molding.

4.6.2 Prepreg Lay-Up

The certified graphite/PMR15 prepreg is removed from storage and allowed to assume room temperature prior to opening the sealed polyethylene container. A "kit" of material is then cut from the prepreg, having polyethylene film on both sides of every laminae. This kit contains all the laminae required for the duct-shell lay-up. The laminae are cut to the configuration described by the engineering drawing. The polyethylene retains the materials "tack" and is removed during the lay-up operation.

The mold is coated with a teflon release agent prior to applying the first set of prepreg laminae; this set comprises the first ply. Methanol is applied to this ply to tack or stick it to the mold surface. Mylar shrink film is applied over the prepreg in a spiral wrap. The film is secured with mylar adhesive tape and shrunk tightly around the prepreg by inserting the entire lay-up mold in a 204° C (400° F) oven for 3 minutes, with the ends of the mold tool sealed to keep the mandrel from heating up. The oven temperature drops immediately when the doors are opened and barely recovers to 204° C (400° F) at the end of 3 minutes. This process debulks the ply to about 0.406 to 0.432 mm (16 to 17 mils) in thickness. The shrink film is removed, and the process is repeated throughout the laying up of all plies. If the material does not tack down adequately, methanol may be applied at the lap edges of the laminae.

After the final ply is layed up and debulked, the shrink film is removed, and a porous teflon release is applied. A spiral wrap of heat-shrinkable fabric tape known as ceconite is then applied and shrunk tightly into position using the 204° C (400° F) oven for 3 minutes.

4.6.3 Oven Imidization

The preform, together with an 8-ply process-control panel, is imidized in an air-circulating oven according to the following schedule:

- Room Temperature to 76.7° C + 5.6° C (170° F + 10° F) at 0.56° C/min (1° F/min)
- Hold for 60 Minutes

- Raise to 135° C (275° F) at 0.56° C/min (1° F/min)
- Remove Immediately From the Oven and Cool to Room Temperature.

Both the heat-shrinkable fabric and the release fabric are removed from the preform, and it is now ready for molding.

4.6.4 Vacuum-Bag-Autoclave Molding

The partially imidized preform is first covered with porous release fabric and then two knit fiberglass cloth "bleeders." Strips of heavy tooling glass cloth are then added parallel with the axis of the tool and overlapped 5 cm (2 in.) axially each. The assembly is held tightly to the preform with a spiral wrap of glass-cloth tape. At each end of the tool, a steel sash chain is wrapped into the bleeder plies to act as a "header" so that the bleeder mechanism can vent to the vacuum ports of the tool. Then, the entire assembly is covered with a vacuum bag made of DuPont's Kapton H film and sealed with a high temperature sealant. Next, the vacuum bag is checked for leaks. A second vacuum bag is made up and applied over the first bag with a ply of 1581 glass-cloth bleeder in between. The second bag is checked for leaks. The assembly is now ready for autoclaving.

The assembly and the process-control preform are connected to the vacuum lines in the autoclave, and the bags are rechecked for leaks. The assembly is then autoclaved according to the following cycle:

- Hold 10.16 cm (4 in.) of Hg vacuum
- Raise temperature to 204.4° C (400° F)
- Hold 204.4° C (400° F) for 15 minutes; then apply full vacuum
- Raise temperature to 238° C (460° F); then apply 1.27 MPa (185 psi)
- In 30 minutes, raise temperature to 252° C (485° F)
- Hold 252° C (485° F) for 30 minutes
- Raise temperature to 307° C (585° F) at 1.11° C (2° F) per minute
- Hold these conditions for 180 minutes
- Release vacuum and pressure before lowering temperature to 65.5° C (150° F) (Figure 36).

After the autoclave cycle, the duct-shell molding is inspected both visually and by UTTSC (ultrasonic through-transmission with a C-scan) read-out. The attenuation of the ultrasonic signal is proportional to the void content of the laminate. A grid pattern is established on the surface of the part where precise attenuation readings are made. These readings are recorded for later calculation of void content (Figure 37).

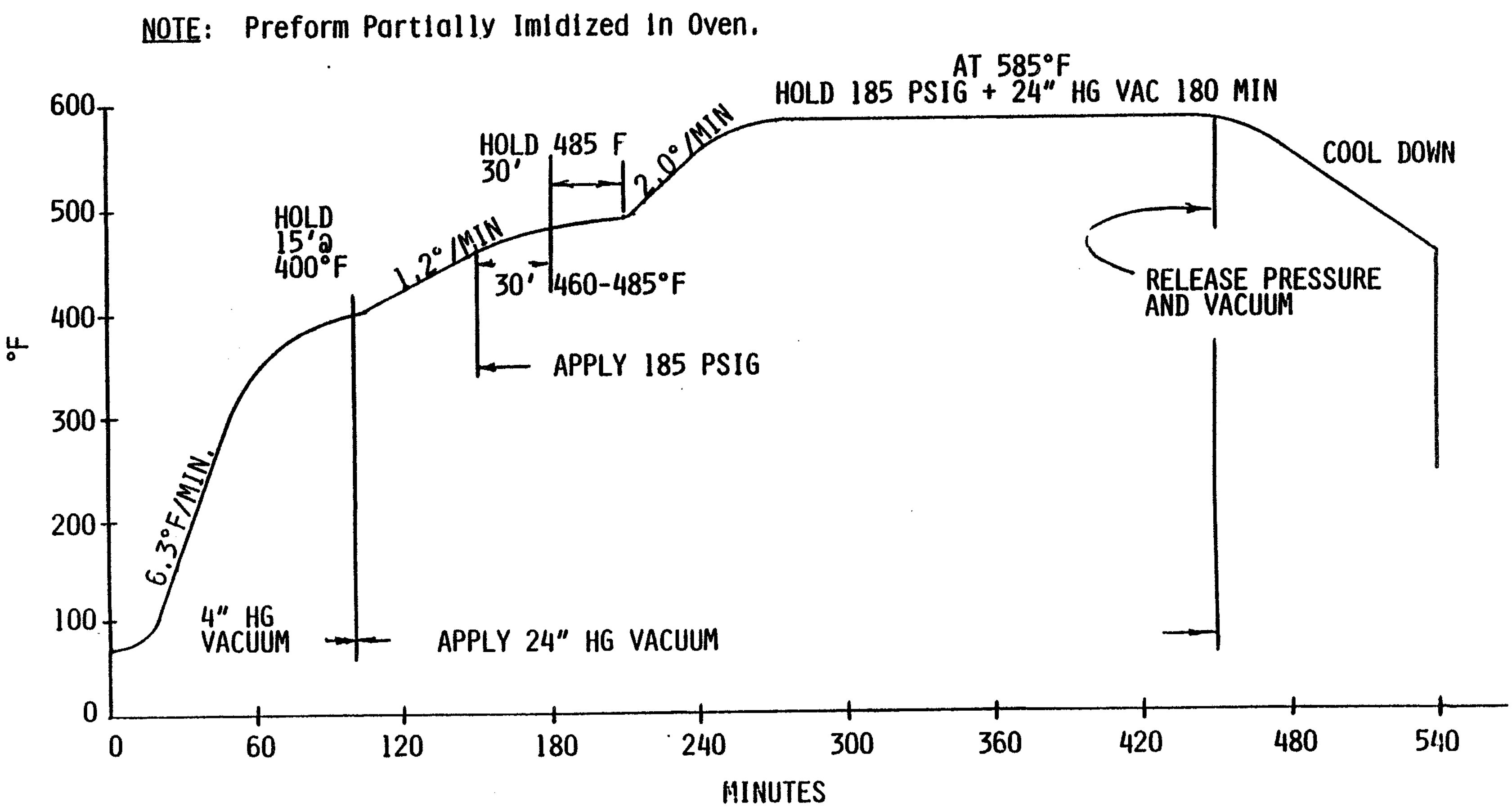


Figure 36. F404 Composite Outer Duct Autoclave Cycle.

DIST FROM AFT END	Top ℄ 0°	60°	100° PLY BUILD UP	120°	153°	Bot ℄ 180°	240°	260° Ply BUILD UP	300°
2"	<1.5%	<1.5%	<1.5%	<1.5%		<1.5%	<1.5%	<1.5%	<1.5%
6"	<1.5%	<1.5%	<1.5%	<1.5%		<1.5%	<1.5%	<1.5%	<1.5%
10"	<1.5%	<1.5%	<1.5%	2.5%		2.0%	<1.5%	<1.5%	<1.5%
14"	<1.5%	<1.5%	<1.5%	2.0%		2.0%	<1.5%	<1.5%	<1.5%
18"	<1.5%	<1.5%	1.5%	3.0%		2.5%	1.5%	<1.5%	1.5%
22"	<1.5%	2.0%	1.5%	4.5%		3.0%	2.0%	<1.5%	1.5%
26"	<1.5%	<1.5%	<1.5%	2.0%	3.5%	3.5%	2.0%	<1.5%	<1.5%
30"	<1.5%	1.5%	<1.5%	1.5%	5.0%	4.0%	2.0%	<1.5%	<1.5%
34"	<1.5%	<1.5%	1.5%	2.0%	5.0%	4.0%	2.0%	<1.5%	<1.5%
38"	<1.5%	2.0%	<1.5%	3.0%		4.0%	2.5%	<1.5%	1.5%
41"	<1.5%	<1.5%	<1.5%	<1.5%		<1.5%	<1.5%	<1.5%	<1.5%

Degrees are CCW (Counterclockwise) from Aft End

Figure 37. The F404 Duct (S/N 80003) Void Content, as Determined from the Attenuation of the Through-Transmission Ultrasonics.

The C-scan is a "grey-scale" read-out of the surface indicating apparent defects and is produced by the attenuation of the ultrasonic signal. The grey scale can be adjusted so as to show extensive detail of void content level (for example, 3%) chosen for recording and, of course, any delaminations. The mapping of the approximate void content at any predetermined level can thus be made.

The duct shell is now ready for the addition of secondary ply build-ups which will serve as reinforcements and dimensional offset for positioning the extensive hardware to be attached to the duct. Axial split-line doublers are also to be made. The build-ups are comprised of the same graphite/PMR15 prepreg as that of the duct shell, and are molded and bonded into position by the autoclave process which procedure, typically, is to:

- Mark the position of build-up areas on the duct shell from precise mylar overlays
- Prepare the surface for bonding using chlorothene solvent, wiping before and after a light grit blast
- Prepare the prepreg kits for the build-ups
- Apply 1-ply of Style 120 glass cloth/PMR15 to the area (50% resin); this material serves as an adhesive
- Apply the build-up plies to the duct shell; dampen them with methanol, if required, to tack them into position
- Vacuum-bag autoclave the assembly, using the process described in Figure 38; this process is used instead of the duct-shell laminate process described above, because of the need for vacuum-bag pressure throughout the imidizing portion of the cycle to hold all build-ups in place.

This process is repeated several times in order to accomplish all of the build-up areas and doublers required. The duct is now ready for machining and the attachment of the metal hardware.

The sequence of the major operations that were performed in the fabrication of the composite duct is shown below:

- Receive prepreg
- Cut prepreg
- Lay-up duct body
- Oven/autoclave cure
- Trim
- Ultrasonic inspection
- Locate positions of thickened-area, ply build-ups
- First lay-up of build-ups for the embossments and doublers

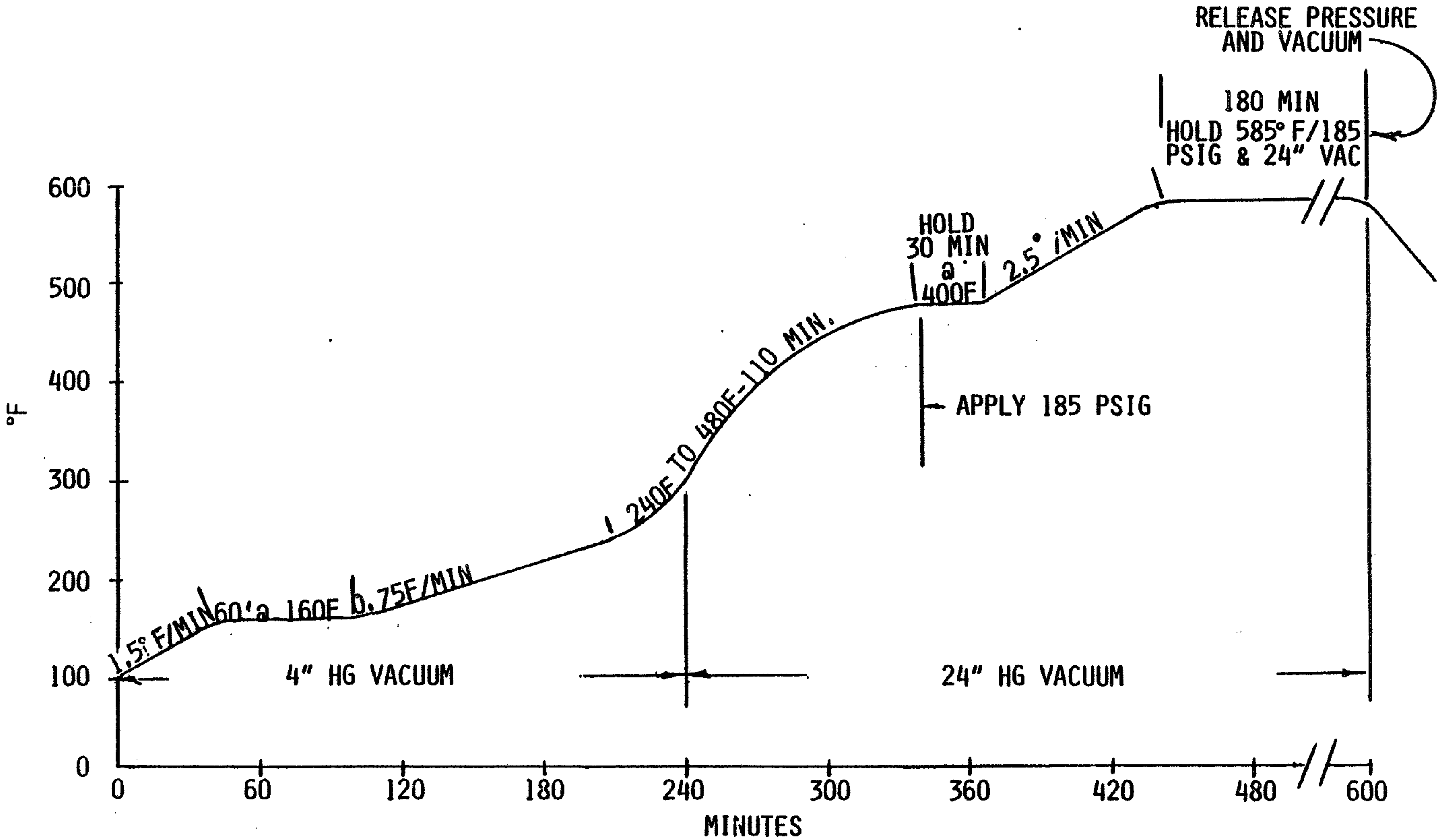


Figure 38. F404 Composite Outer Duct Secondary Lamination Autoclave Cycle.

- Autoclave cure
- Second lay-up of ply build-ups for the embossments and the stiffeners
- Autoclave cure
- Third lay-up of ply build-ups for the embossments and axial stiffener covers
- Autoclave cure
- Drill doublers (Figures 39 through 42)
- Cut duct cylinder into upper and lower halves (Figures 43 through 46)
- Drill and rivet flanges (Figures 47 and 48)
- Mill flats for clevis and uniball
- Drill and rivet clevis and uniball
- Lay-up epoxy/glass ID fixture
- All other machining
- Remove ID fixture
- Ultrasonic inspection (Figure 49).

The axial stiffener was manufactured from the same materials employing the same process technology utilized for the basic duct laminate. Figure 42 illustrates the axial split-line stiffeners. After these stiffeners were molded and trimmed to size, they were located into drill fixtures (Figure 39) which were located to the composite duct. The holes in the axial stiffener and duct were drilled at the same time. Figure 41 shows the tool, positioned along the axial split line, that was used to drill holes in the duct and in the axial stiffeners. The next operation consisted of installing titanium rings (Figure 47) on the composite duct shown in Figure 48.

The duct was then sent to the GEAE facility in Everett, Massachusetts for the finish machining operations. This is the facility that machines all of the current metal F404 outer ducts. This machining has been completed (Figure 50) and the duct returned to Albuquerque.

The remaining operations to complete the duct consist of the following:

- Apply a seal coating to the duct
- Assemble and adhesively bond the metal inserts into the various build-up pads on the external and internal areas of the duct
- Complete the postcure of the duct
- Install metal studs
- Identify the completed duct
- Conduct final inspection and ship duct for testing.

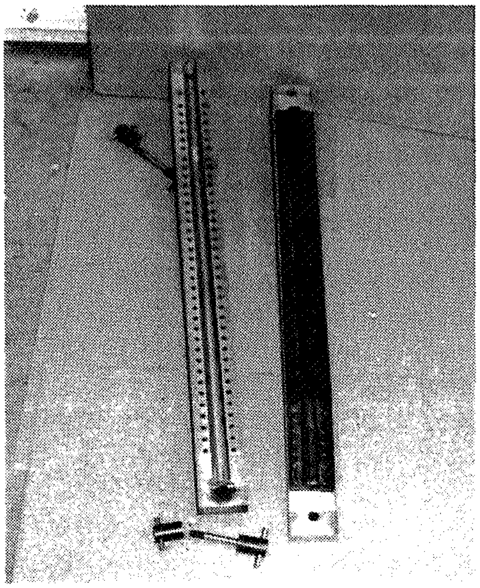


Figure 39. Axial Stiffener Drill Fixture.

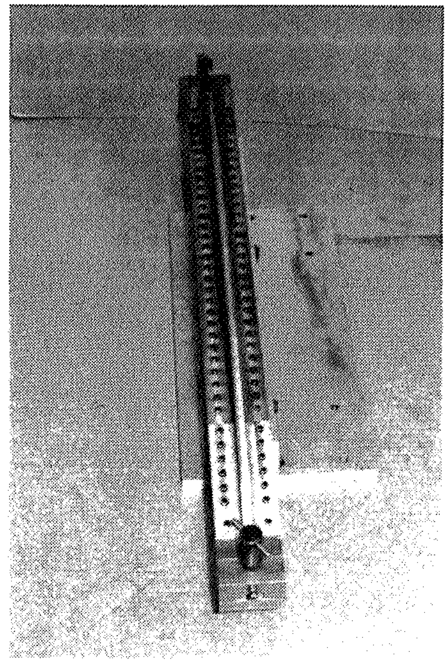


Figure 40. Axial Split-Line Fixture.

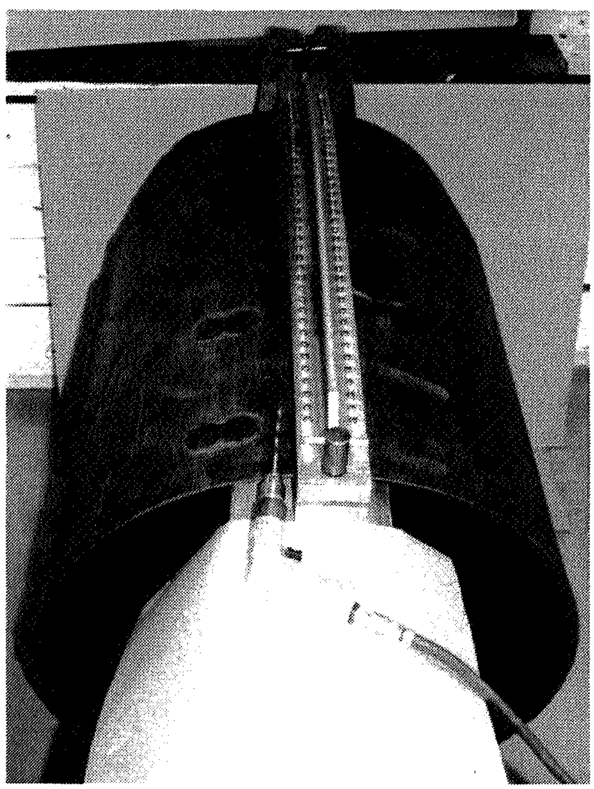


Figure 41. Axial Split-Line Fixture Indexed to the Composite Duct.

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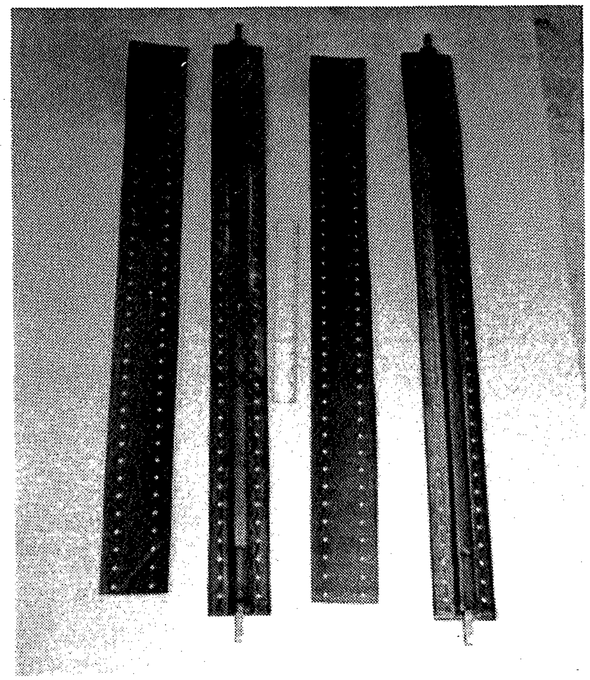

Figure 42. Axial Split-Line Stiffener.

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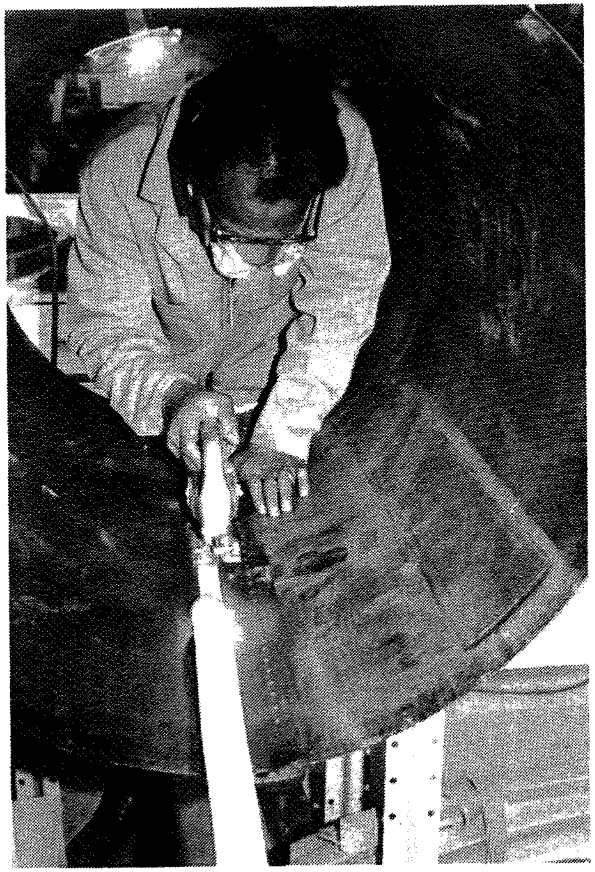

Figure 43. Machining the Duct Into Halves.

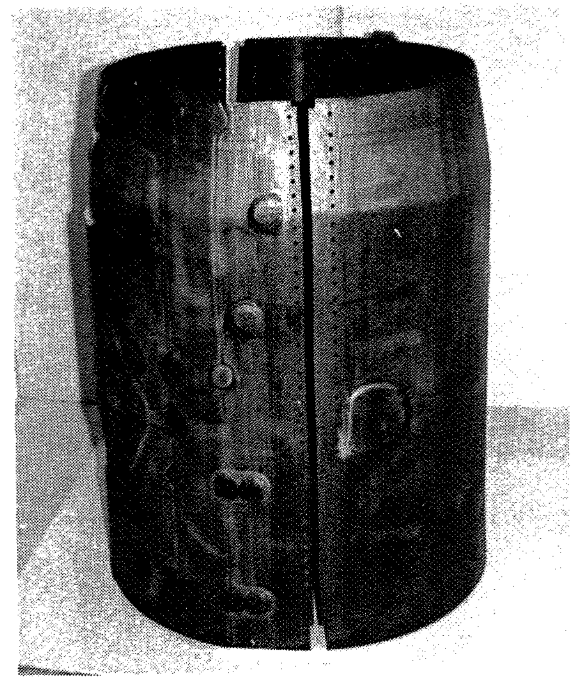

Figure 44. Composite Duct Cut Apart at the Split-Line.

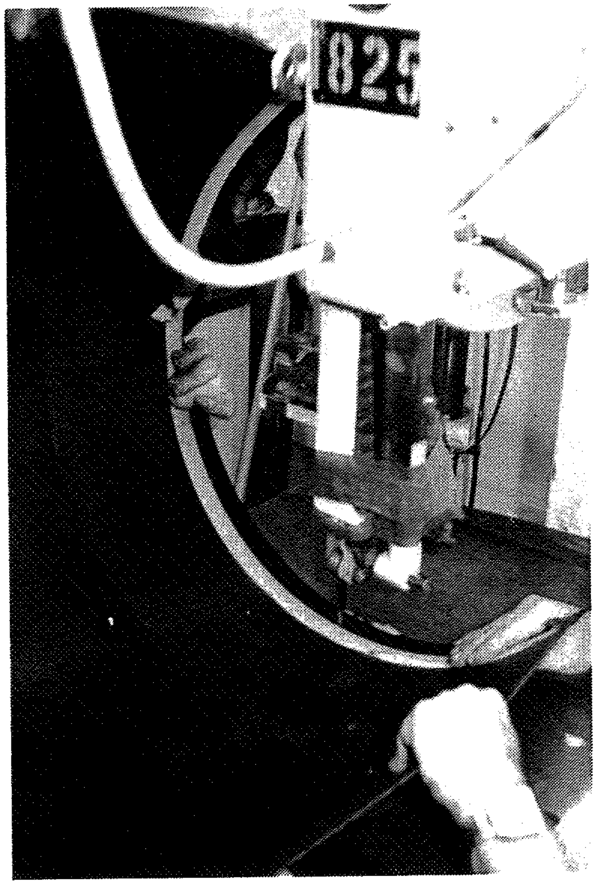

Figure 45. Machining Forward End of the Composite Duct with a Band Saw.

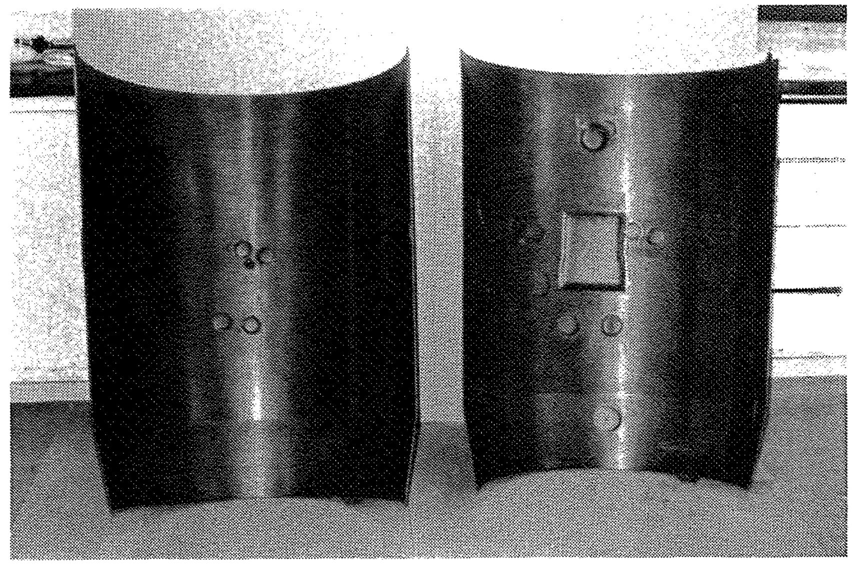

Figure 46. Finished Axial and End Trimmed Composite Duct.

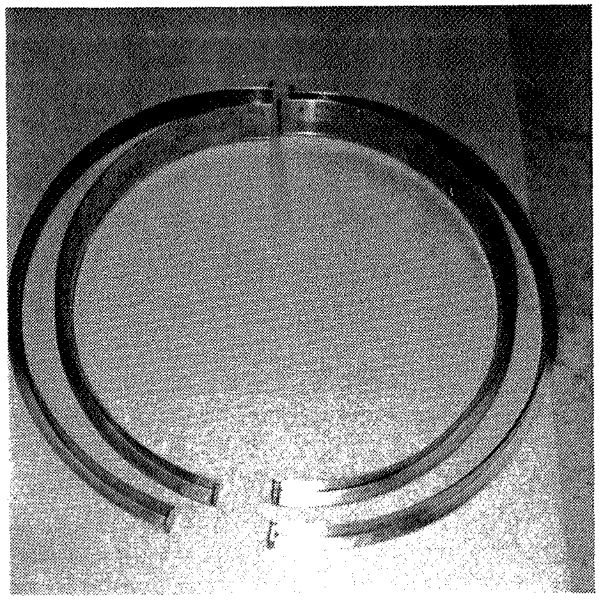

Figure 47. Titanium Forward and Aft Attachment Rings.

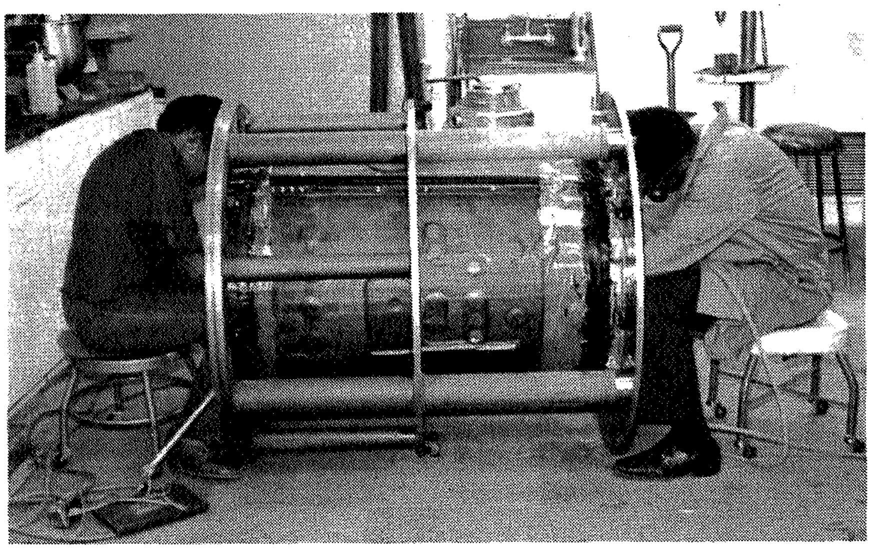

Figure 48. Duct in the Assembly Fixture.

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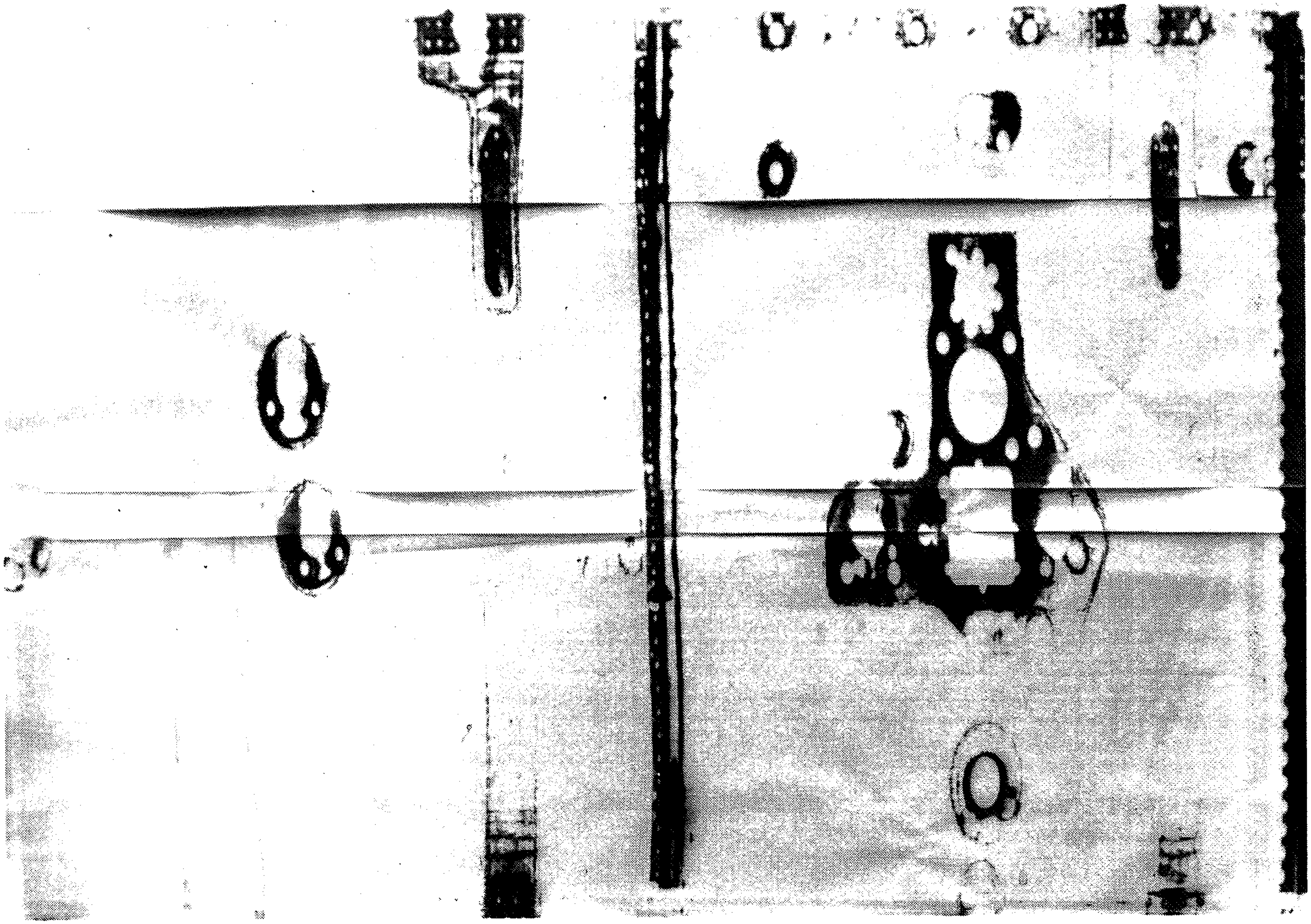

Figure 49. Ultrasonic Inspection Record.

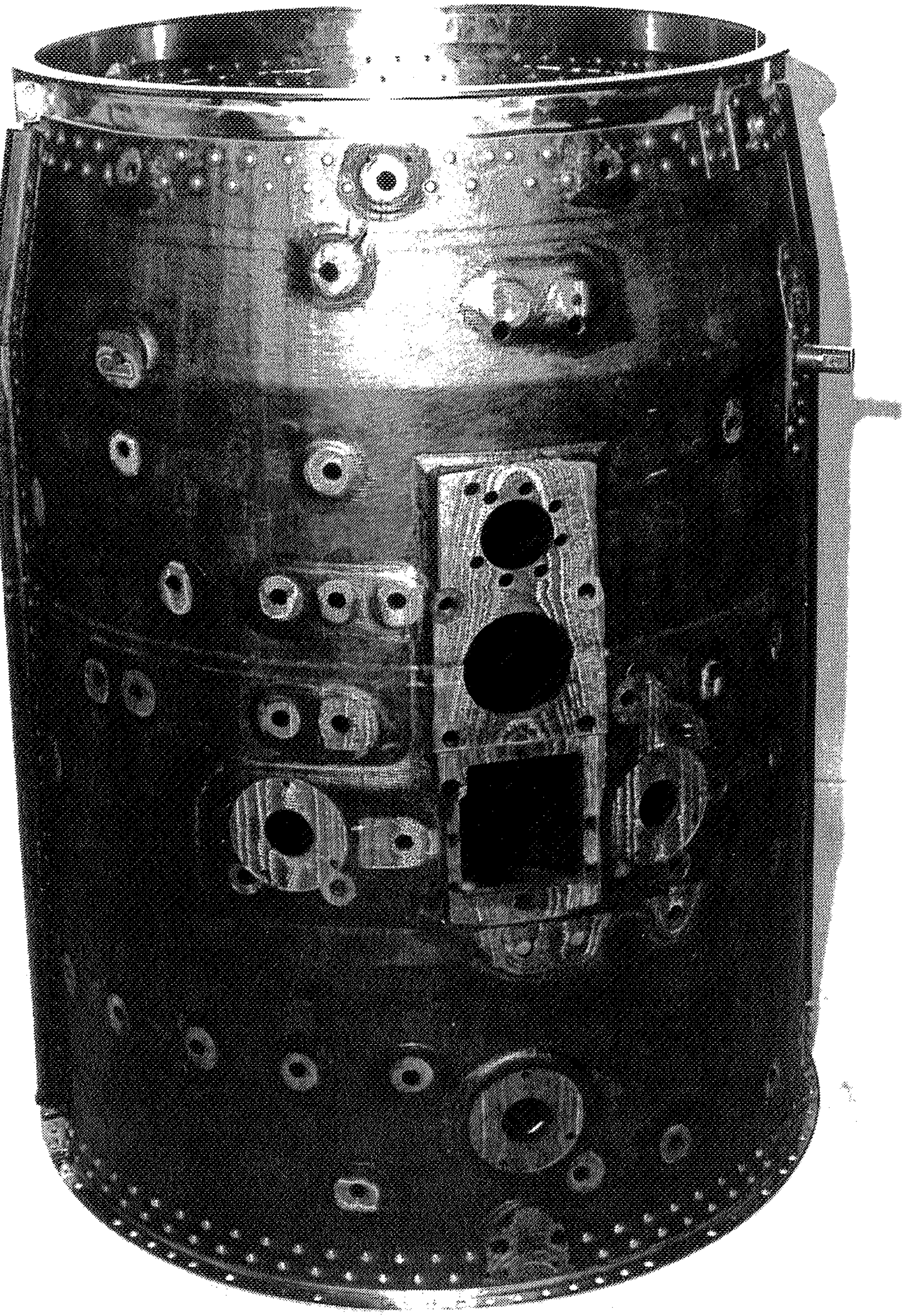

Figure 50. Composite Duct After Machining.

A pictorial sequence of the previously described duct fabrication cycle is provided herein as Figures 51 and 52.

4.6.5 Composite Duct Quality

Of the several basic duct shells fabricated during this program, the one selected for completion was inspected twice by UTTCS (ultrasonic through-transmission with a C-scan) read-out. It was first inspected after the basic shell was made and before any build-ups were incorporated. At this time, attenuation values of the ultrasonic signal were used to establish the void content of the laminate. Previous work had been done to confirm this technique. A grid pattern was established on the surface of the part, and precise attenuation readings were taken. A grey-scale read-out of the laminate was also produced by the attenuation of the ultrasonic signal. The grey-scale read-out was used to visually detect any defect areas, and the attenuation values were used to show the magnitude of the void content. Figure 53 tabulates results of the void content which was determined from the attenuation readings of the through-transmission ultrasonic signal.

The second UTTCS inspection was performed after all of the build-ups were processed on the duct and after the machining was completed. The results of this inspection were presented in Figure 49, which is the UTTCS grey-scale read-out of the finished machined duct. The dark areas in Figure 49 represent build-ups on the duct.

4.6.6 Additional Duct Fabrication

Implementing the processes described above, a second duct was fabricated with titanium end flanges. This duct was used for static test purposes as described in Section 4.7. In addition, a duct incorporating integral composite end flanges (developed in Task XI) was fabricated by the above process. This duct also was used for static testing as is discussed in Section 4.7.

4.7 Duct Testing

This section discusses the testing that was conducted on the duct assemblies completed during this program. These ducts were subjected to both factory-engine and static-load testing.

4.7.1 Factory Engine Test

A full-scale duct with titanium end flanges was fabricated in 1981 under Task X of this program. This duct was proof-pressure-checked successfully to 150% of its maximum design operating pressure. Installed on factory test engine No. 023, this duct went to test on August 25, 1981; a total of 304 AMT hours was accumulated upon completion of the scheduled testing. This duct was later installed on other factory test engines and accumulated a total of over 1900 hours of engine operation. The part was inspected and was still suitable for further engine operation. However, the decision was made to terminate further testing of this duct, since it was determined that ducts with integral composite end flanges would be more suitable for a production design.

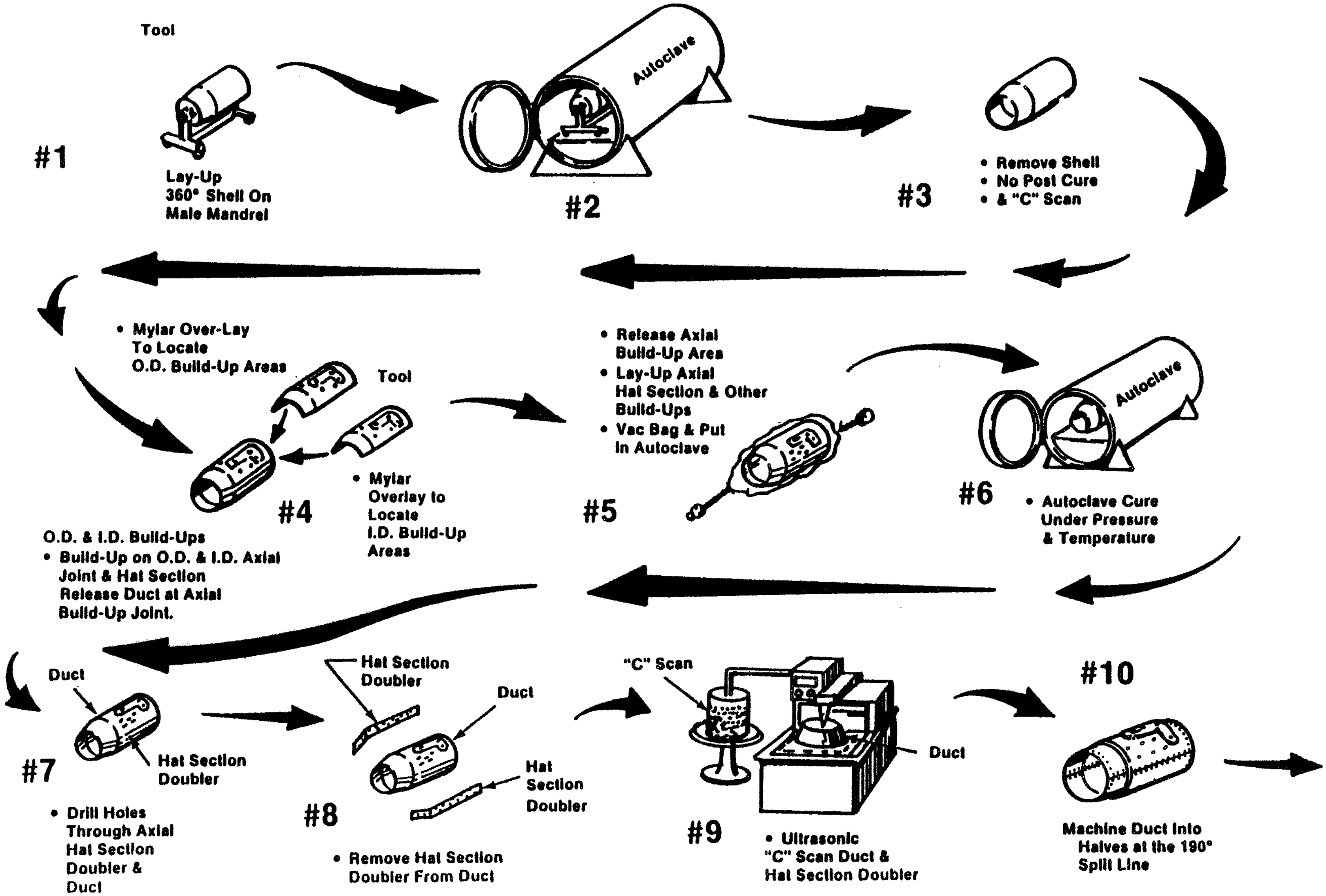

Figure 51. F404 Outer Duct Fabrication Sequence (Steps 1 Through 10).

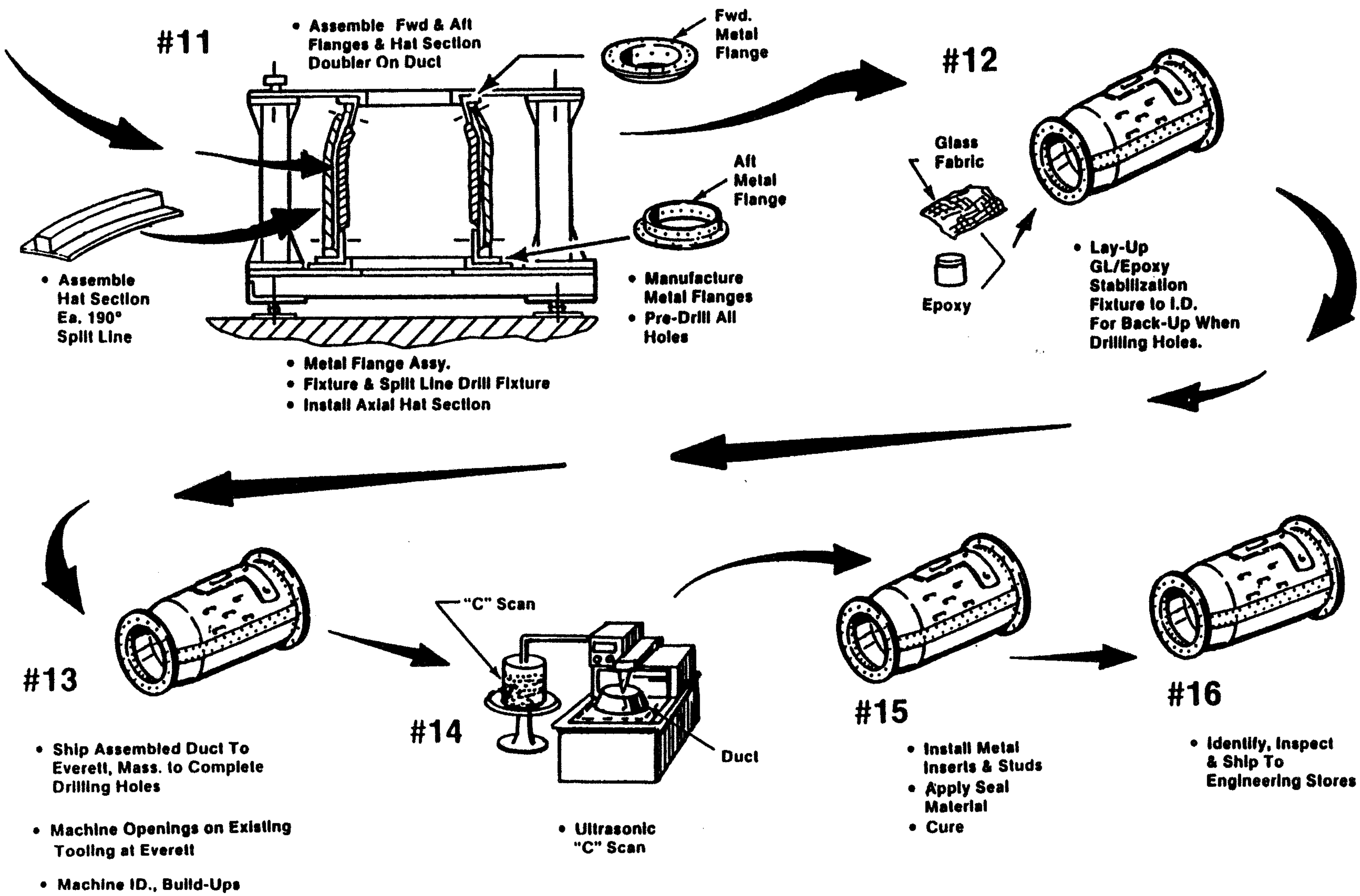

Figure 52. F404 Outer Duct Fabrication Sequence (Steps 11 Through 16).

• Degrees are CCW (Counterclockwise) from Aft End

DIST FROM AFT END	Top ℄ 0°	60°	100° PLY BUILD UP	120°	153°	Bot ℄ 180°	240°	260° Ply BUILD UP	300°
2"	<1.5%	<1.5%	<1.5%	<1.5%		<1.5%	<1.5%	<1.5%	<1.5%
6"	<1.5%	<1.5%	<1.5%	<1.5%		<1.5%	<1.5%	<1.5%	<1.5%
10"	<1.5%	<1.5%	<1.5%	2.5%		2.0%	<1.5%	<1.5%	<1.5%
14"	<1.5%	<1.5%	<1.5%	2.0%		2.0%	<1.5%	<1.5%	<1.5%
18"	<1.5%	<1.5%	1.5%	3.0%		2.5%	1.5%	<1.5%	1.5%
22"	<1.5%	2.0%	1.5%	4.5%		3.0%	2.0%	<1.5%	1.5%
26"	<1.5%	<1.5%	<1.5%	2.0%	3.5%	3.5%	2.0%	<1.5%	<1.5%
30"	<1.5%	1.5%	<1.5%	1.5%	5.0%	4.0%	2.0%	<1.5%	<1.5%
34"	<1.5%	<1.5%	1.5%	2.0%	5.0%	4.0%	2.0%	<1.5%	<1.5%
38"	<1.5%	2.0%	<1.5%	3.0%		4.0%	2.5%	<1.5%	1.5%
41"	<1.5%	<1.5%	<1.5%	<1.5%		<1.5%	<1.5%	<1.5%	<1.5%

Figure 53. Void Content Determined from the Attentuation of the Through-Transmission Ultrasonics.

4.7.2 Static Load Tests

A second full-scale duct with titanium end flanges was fabricated during early 1982. This duct was inspected and then installed in a static test vehicle. Vehicle setup and instrumentation was completed during September, with the static test commencing shortly thereafter.

The test vehicle was nonredundantly supported in the test stand at three mounting points, similar to a right-hand engine in an aircraft. The fixtures were designed so that the aft mount would support only vertical loading, but the left front mount would support load in all three directions. The right front mount was identical to the left, except that it did not provide any significant side restraint.

External loads were applied to the test vehicle by use of a 6-channel, automatic hydraulic loading system. Hydraulic actuators with load cells in series were connected to the test fixture and applied the following loads:

- Channel 0 - Load application forward of No. 1 bearing in the radial direction
- Channel 1 - Same as Channel 0, except load was applied aft of No. 5 bearing
- Channel 2 - Simulated afterburner radial inertial load
- Channel 3 - Simulated thrust on the No. 1 bearing
- Channel 4 - Simulated axial load from afterburner
- Channel 5 - Simulated thrust load on the turbine frame and core shell.

The duct was static-tested to 100% and 150% of the maximum, worst-case maneuvering loads without failure. The duct withstood the 150% flight maneuver loads with no evidence of cracking or buckling. In an attempt to determine the buckling margin, 210% of the worst-case maneuver flight loads was applied. This test was terminated due to facility limitations with no sign of duct failure. The highest measured stress in the duct was 79% of the material allowable. Table 12 presents an overall summary of the tests performed and the maximum stress for each test.

A full-scale duct with integral composite flanges was fabricated under Task XI; this duct was instrumented and pressure tested to 150% of the duct design pressure. There was no evidence of material damage to either the duct itself or to the composite flanges. It was concluded that this type of design was suitable for use in a production design of the F404 outer bypass duct.

Table 12. Overall Summary of Tests Run and Maximum Stresses.

Log Sheet	Flight Maneuver	% Load	S/G No.	Max* Stress, psi	Stiff** Split Line	Plane** Split Line
1&2	9	100	14	-2632	X	
3	9	100	14	-3794		X
4	9	150	14	-3983	X	
5	9	150	14	-5418		X
6	9	210***	14	-5439	X	
7	16	100	6	1953	X	
8	16	100	6	2016		X
9	16	150	6	2100	X	
10	16	150	6	2135		X
	Right Side Loading					
11	9	100	6	2170	X	
12	9	150	12	2975	X	
	VG Actuator Loading					
13	Simulated	22	8	-4403	X	
14	Actual	100	1	1771	X	
15	Individual application of 100% loads for flight maneuver No. 9					
16	Individual application of 100% loads for flight maneuver No. 16					

*Note that 150% load stresses are not necessarily 1.5 x the 100% load stresses because although the G loads increases by 1.5 the thrust loads are not significantly greater.

**Plane and stiff refer to the type of plate which was used to join the composite duct split lines:

Stiff - The plate had a rectangular hat section down the outside center of the plate which simulated the radial and axial stiffness of the split line flange on current outer duct.

Plane - Just a plane unstiffened composite plate.

***An attempt was made to buckle the duct but test fixture limits were reached at 210% loading.

5.0 TECHNICAL DISCUSSION - FAN STATOR CASE AND VANES

5.1 Objective

Based on the success of the F404 composite outer duct effort, it was decided to investigate the prospect of applying this technology to a more complex structural system. Therefore, Task XII was added to the program with the objective of evaluating the application of the graphite/PMR15 system to the F404 fan stator case and stator vanes. This evaluation was to be made based on the projected weight and costs of the composite design versus that of existing production hardware. Subcomponents representing critical areas of the composite design were to be fabricated and tested to aid in the selection of the final projected configuration.

5.2 Approach

The approach taken to meet the program objection was, first, to establish the baseline design and operational requirements, and then to develop composite design concepts that would meet these requirements while taking advantage of the unique properties of the composite materials. In a number of areas where information on specific composite properties or concepts did not exist, subcomponent test programs were developed and executed to provide the required data.

Results of these investigations were combined with specific analyses of critical case/vane areas and the lessons learned from the work done on the F404 composite duct portion of the program to produce a composite design for the F404 fan case and vane structure. This design was then subjected to a weight and cost analysis and the results compared to the baseline configuration to determine what benefits, if any, can be attained by using an advanced composite material in this application.

5.3 Baseline Definition and Requirements

The baseline structure selected as the basis for evaluation during this phase of the program was the fan stator assembly of the GE-F404 engine.

All of the composite design concepts that were evaluated during the feasibility program had to meet the basic design requirements of the existing titanium fan case and vane structure. This structure defines the stator aerodynamic flowpath of the fan module and contains three rows of vanes, all of which are fixed. A schematic of this structure is shown in Figure 54, and a photograph of one half of the assembly is presented as Figure 55.

The fan casing performs several major functions other than the outer fan flowpath and pressure vessel. The casing is the prime structural support transferring the overhung fan static and dynamic loadings from the front frame to the midframe. It also supports the cantilevered stator vanes (Stages 1, 2, and 3) in their proper relation to the fan rotor assembly. The casing also provides support for the external engine configuration hardware, accessories, and for the front frame IGV (inlet guide vane) variable geometry trunnion.

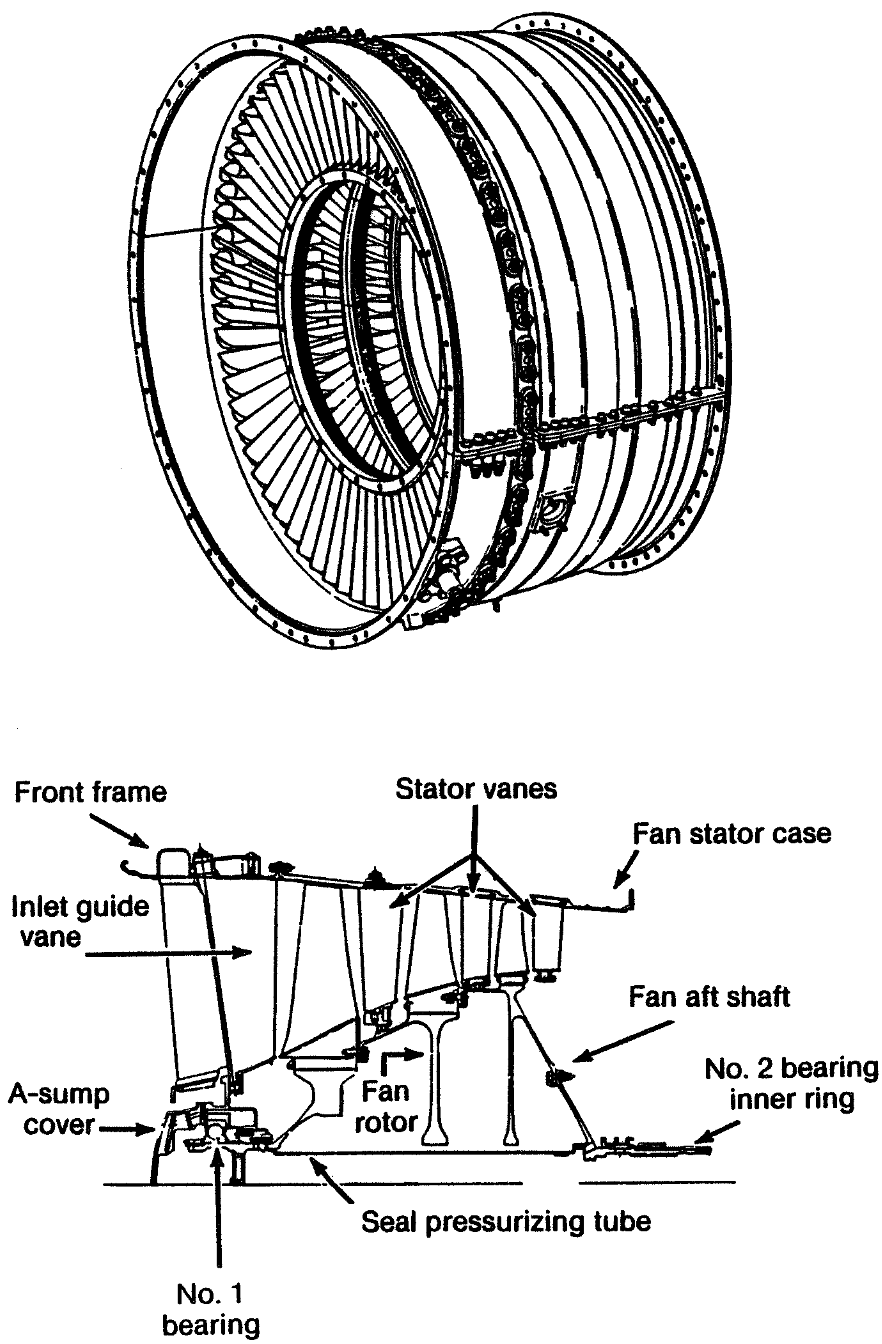

Figure 54. Fan Module Cross Section and Fan Stator Trimetric.

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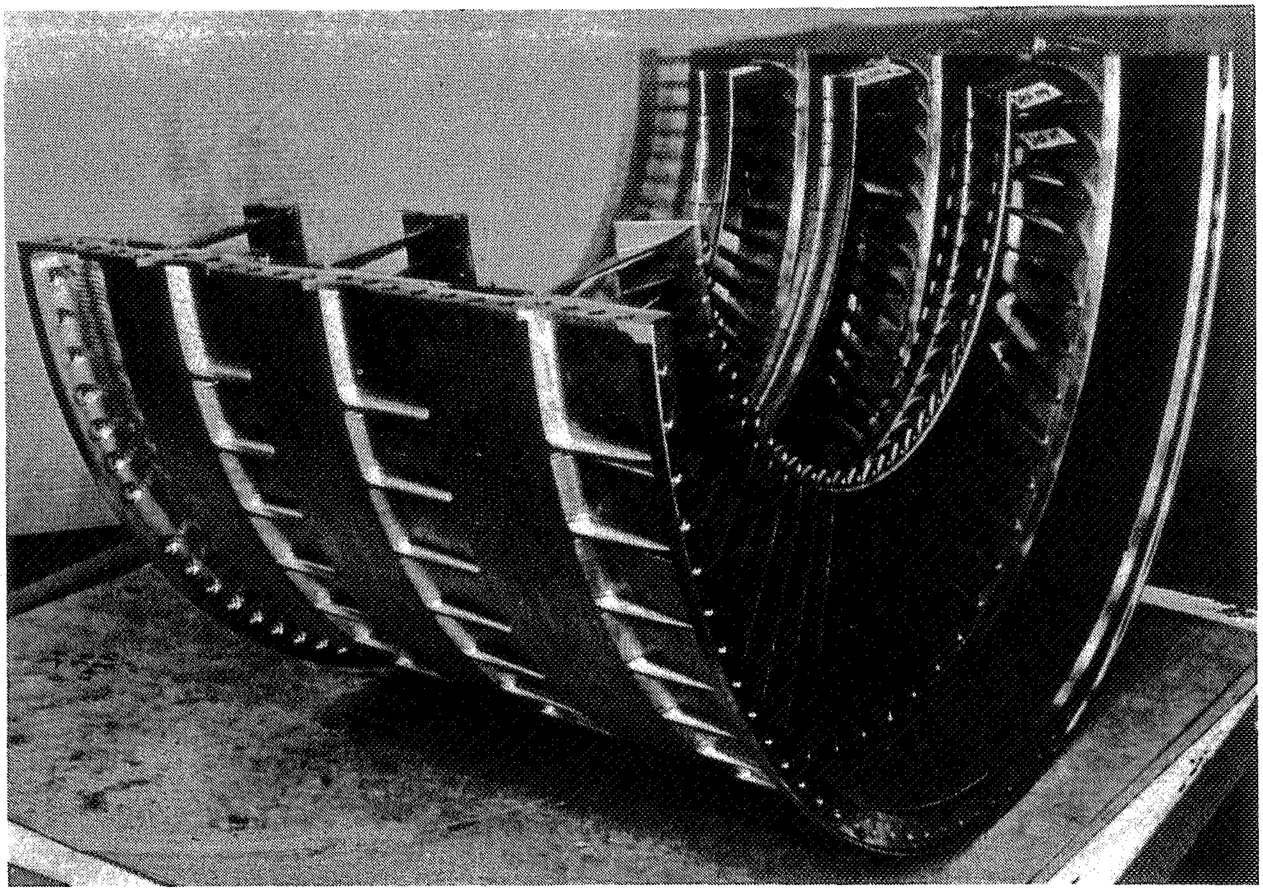

Figure 55. Titanium Fan Case and Vane Assembly.

The fan casing must also provide a shield capable of containing a blade released from the fan rotor due to a failure in the airfoil root fillet radius and retain sufficient structural strength to handle the unbalanced loading during shutdown.

Further, the fan casing and vanes must also be capable of providing service for a minimum of 4000 F-18/F404 engine flight hours. This includes the capability to withstand the temperature and pressure extremes of the engine operating envelope and the environmental hazards, as required by the F404 specification, for sand, water, and ice ingestion and the corrosive salt water environment. The fan casing and vanes must feature ease of maintenance and provide accessibility to the installed fan rotor by removing one of the fan casing halves and accessories.

Based on the above requirements, the composite approaches were developed and evaluated for both weight and cost-effectiveness versus the existing titanium assembly.

5.4 Major Areas of Investigation

Current composite capabilities and design techniques were examined with respect to the requirements defined in Section 5.3. As a result of this examination, five major areas were identified as requiring further investigation and development before the overall composite structures could be defined. The areas concerned the following:

1. Lightweight containment for split casings
2. Composite vane development
3. Vane shroud development
4. Shroud attachment methods
5. Flange evaluation.

The results of the work performed in these areas are discussed in detail in the following paragraphs.

5.4.1 Containment Development

With the use of an advanced composite fan case, it was imperative that some means be provided for the containment of released fan blades. In the baseline configuration, the thickness of the titanium case was thickened to provide this feature; however for the composite case, it was not feasible to increase its thickness enough to provide containment protection due to the low energy absorption characteristics of the material, nor was it practical to add a secondary titanium or steel containment ring due to weight considerations. It was, therefore, decided to utilize the lightweight Kevlar containment concept developed under NASA contracts (References 1 and 2). That concept utilizes dry Kevlar cloth wrapped over a 360° honeycomb sandwich structure which, in addition to supplying the required strength and stiffness for the case, provides a nesting area for any blade or blade fragments and also prevents the dry Kevlar material from interacting with the fan rotor after a containment event.

Two requirements of the F404 fan case design dictated that the basic containment concept be somewhat modified from those previously developed. The first major difference concerns the fact that the fan case must be split; therefore, the containment system must either be split or removable, rather than the permanent 360° configuration as previously developed. Another difference is in the space available to install the containment system. Previous designs utilizing the lightweight containment concept had rather generous amounts of space available in which to contain and nest the released blade; however, due to installation and configuration requirements of the F404 engine, there is no room in which to incorporate a nesting area or to keep the containment material (dry Kevlar) out of close proximity to the rotor.

This latter situation creates a problem, however, in that previous tests have shown that if the dry Kevlar containment material is close to the rotor during a blade-out event, it can be drawn into the rotor path and interact with the rotor, thus causing extensive secondary damage. In an

attempt to improve this situation, a new, lightweight, containment material called Armoflex was evaluated. Armoflex is manufactured by laminating Kevlar fabric with an elastomeric matrix material which, in turn, holds the Kevlar fabric together, thus aiding attachment and enhancing fraying resistance on impact.

A ballistic-impact test program was performed by the University of Dayton Research Institute to determine the relative ballistic efficiency of Armoflex and dry Kevlar cloth. A compressed gas cannon was used to propel simulated blade projectiles into the test panels; an impact angle of 60° to the panel surface was chosen to simulate fan case impact. Projectile velocity was measured before impact by a dual-laser, velocity-measuring device; and, utilizing high speed photography, the impact response was recorded.

Figure 56 compares the dry Kevlar and Armoflex impact tests results. Projectile energy versus number of material plies are plotted showing the Armoflex and dry Kevlar. From these results, one can obtain the threshold containment energy level between contained and uncontained impact for a given number of material plies. From past containment studies (Reference 1), the relation between the required containment thickness and impact energy has been shown to follow the relation $T = KE$; where: T is the containment thickness, K is an empirical constant, and E is impact energy.

Test results indicated that Armoflex was better than the dry Kevlar (on the basis of per ply); however, due to the weight added to Armoflex by the elastomeric matrix, Kevlar proved to be more effective on the basis of weight. Because the Armoflex did exhibit good resistance to raveling, it was decided that a combination of Armoflex and Kevlar be employed for the containment system, wherein the dry Kevlar would be sandwiched between several plies of Armoflex. This approach provided a semi-rigid structure which could effectively contain a released blade and protect against the possibility of rotor/containment interaction. Testing also demonstrated that this material combination could be bolted to end plates and still resist impact without tearing out the material in the area of the bolts. This feature allowed the use of a split containment system where the containment material was attached to the titanium flange back-up plates as shown in Figure 57. Consequently, this approach solved the problems of space, as well as the requirement for a split casing.

5.4.2 Composite Vane Development

One of the major areas of interest in this program was the potential application of advanced composite materials to the fan stator vanes. This study was limited to the first-stage stators since Stages 2 and 3 were considered to be too small and too thin for effective application of composite materials. The material-form selected for use in the vane was unidirectional graphite tape material impregnated with the PMR15 matrix system. Intermediate modulus and high modulus fibers were analytically evaluated. The primary design consideration was the frequency responses of the vane when compared to the excitation sources. In addition to fiber material variation, a number of fiber-orientation combinations were also evaluated. This evaluation was accomplished using a model (Figure 58) to predict the resonant frequency

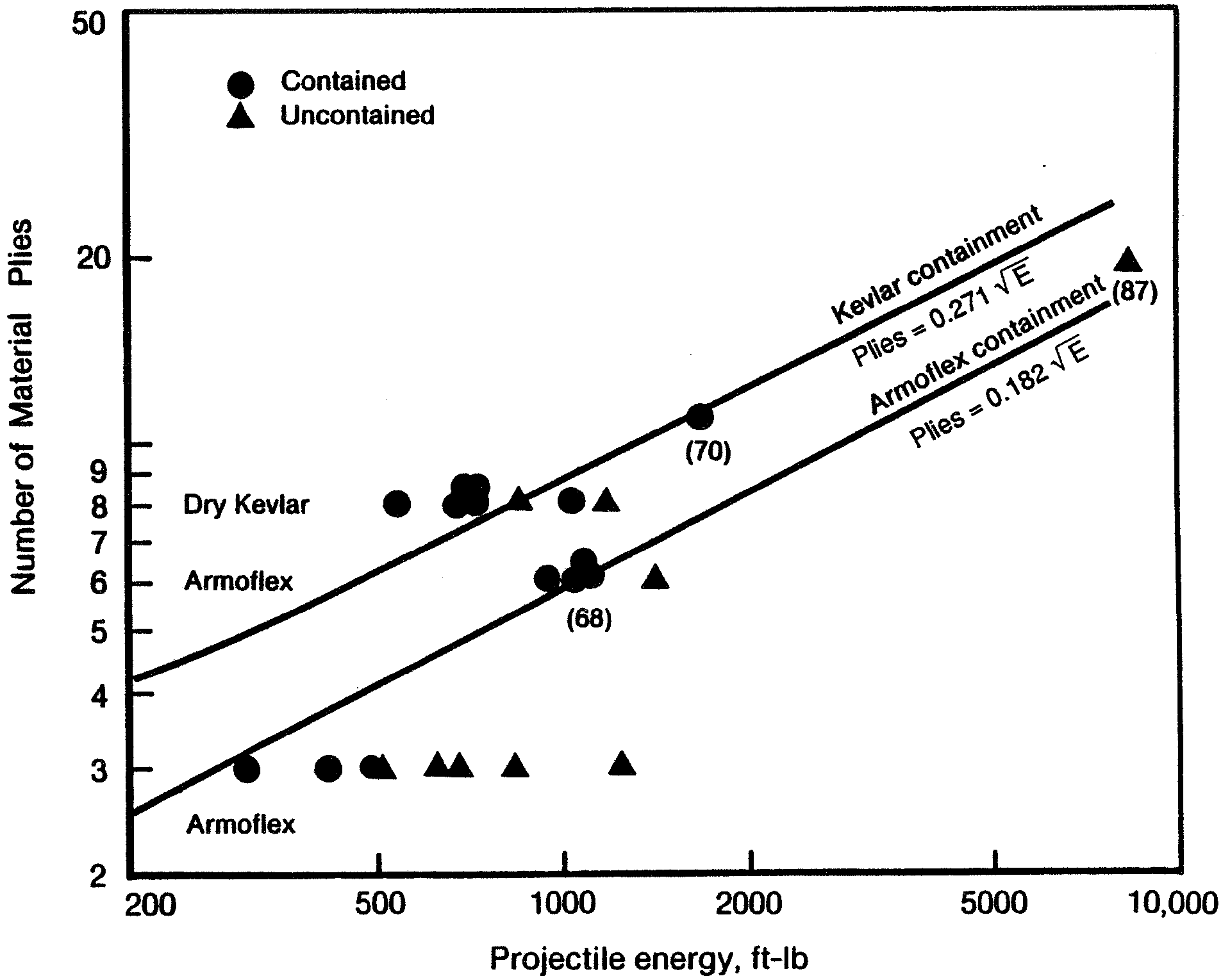

Figure 56. Ballistic-Impact Test Results.

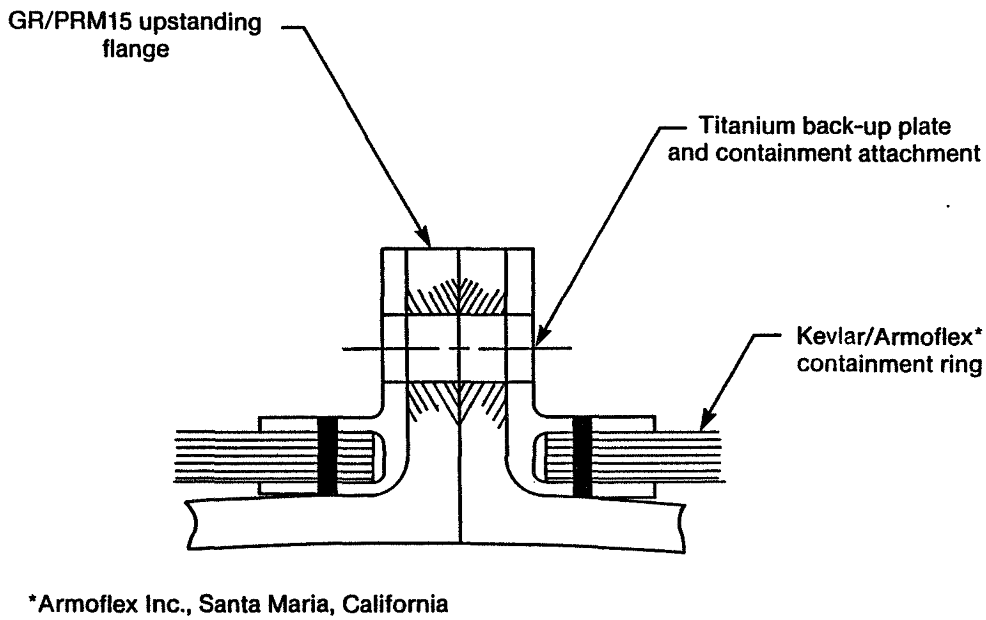

Figure 57. Configuration of Split Flange.

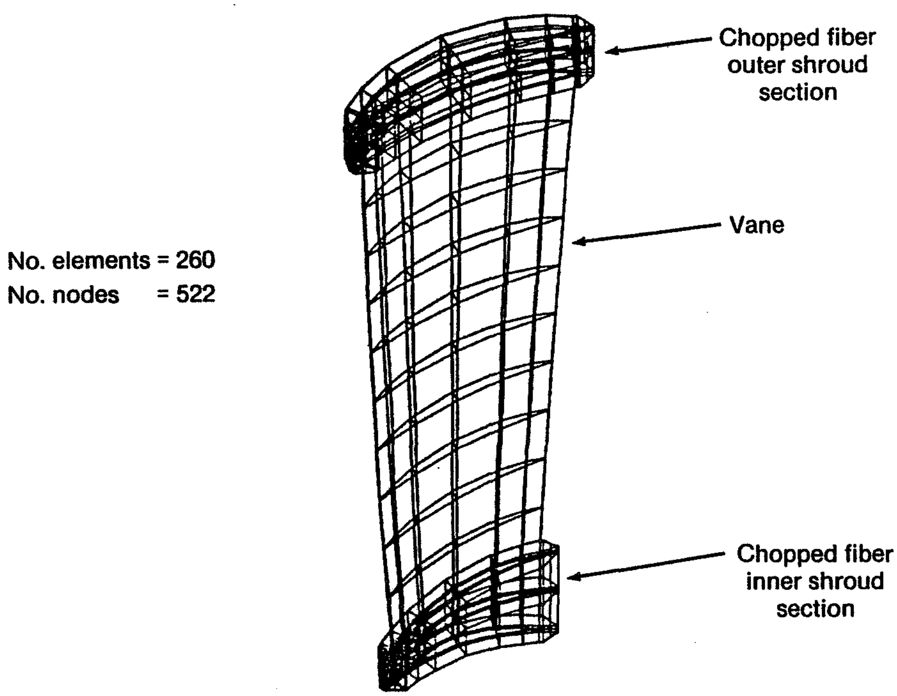

Figure 58. Stage 1 Vane/Shroud Finite-Element Model.

characteristics of a titanium vane and several lay-ups of a PMR15/graphite composite vane. This analysis has shown that an acceptable configuration for a composite Stage 1 vane would be a 0/90/45/-45 lay-up of intermediate modulus graphite/PMR15 tape.

Figures 59 and 60 are Campbell diagrams showing a titanium and a 0/90/45/-45 PMR15/graphite composite vane. As evidenced by the Campbell diagrams, these two vanes are similar, with the resonant frequencies of the composite vane slightly higher than those of the titanium vane. In both cases, first flex is satisfactorily above 3/rev of the rotor. The predominate driving force for the Stage 1 stator is the 32/rev frequency from the Stage 1 rotor blades; for both the titanium and composite vanes, the 32/rev frequency crosses the first and second flex/torsion modes below 70% power. Two-stripe frequency for both the composite and titanium vanes also has good margin above the 32/rev frequency at 109% power.

Several vanes were built and frequency-tested, but the results were inconclusive due to excessive test scatter. The results of this study indicated that it was aeromechanically feasible to utilize composite materials for the F404 first-stage stator vanes.

5.4.3 Vane Shroud Development

Once it was shown that composite stator vanes could be used in this application, it was necessary to select an outer shroud material that would meet the design requirements and be compatible with composite vanes and casing. It was felt that, due to the characteristics of the selected vane material, the method utilized to install the metal vanes would not be practical for the composite vanes and that a bonded approach would be more practical. Therefore, one of the requirements of the shrouds to be used with the composite vanes was that they provide sufficient bond area to allow the vanes to be bonded to the shrouds.

In order to keep the cost and weight of the shrouds to a minimum, it was decided to utilize a composite material that could be either injection-molded, such as Torlon, or compression-molded, such as graphite/PMR15 molding compound. After some preliminary studies, it was decided to select the graphite/PMR15 molding compound due to its better thermal stability.

One of the methods considered for attaching the shrouds (and flowpath liners in some configurations) was to mechanically attach these parts to the composite casing. To accomplish this, it was necessary to develop and evaluate some means of installing threaded inserts into the shroud material. Figure 61 illustrates some of the methods evaluated. Based on torque-out and pull-out tests, it was decided to utilize an insert that could be screwed into a tapped hole. Tests were conducted to determine whether these inserts should also be bonded-in as well as screwed in, and to see if the length of the reinforcing graphite fiber had any effect on the pull-out and torque-out capability. Figure 62 summarizes typical test results. It was concluded from these tests that the inserts should be bonded-in and that there was no conclusive difference in the insert-retention capability between the fiber lengths investigated.

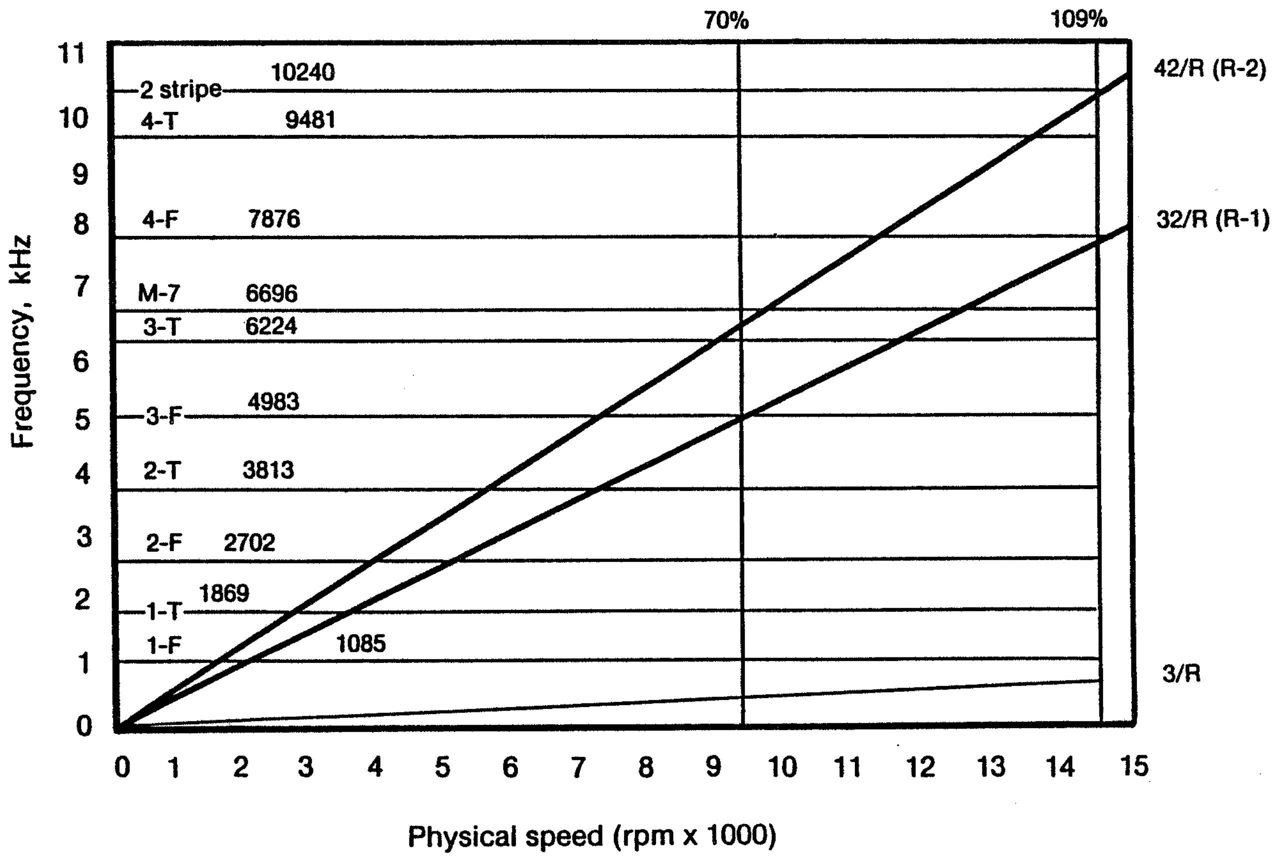

Figure 59. Stage 1 Resonant Frequency FF (Fast Fourier) Analysis, Titanium Vane.

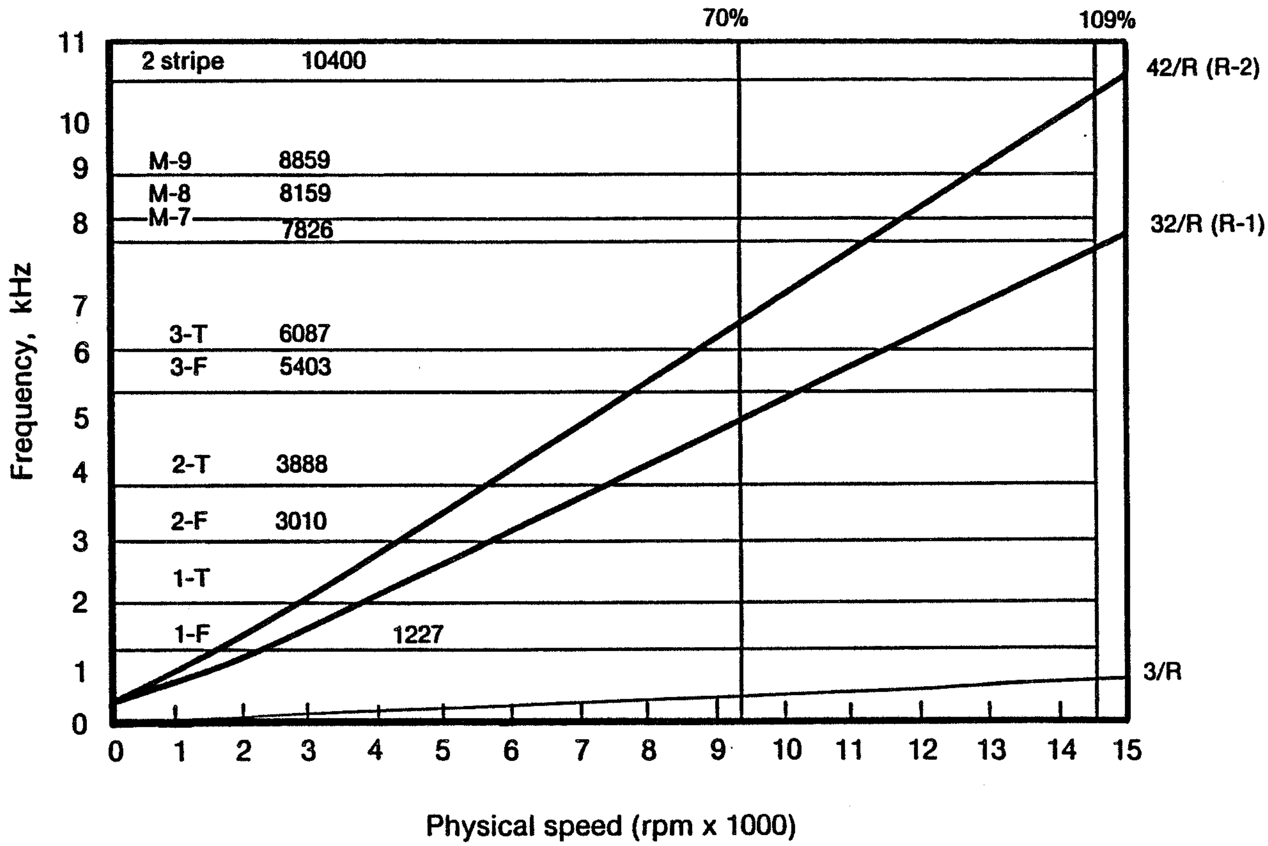

Figure 60. Resonant Frequency Analysis (Fast Fourier) of Stage 1 (0/90/45/-45) PMR15/Graphite Vane.

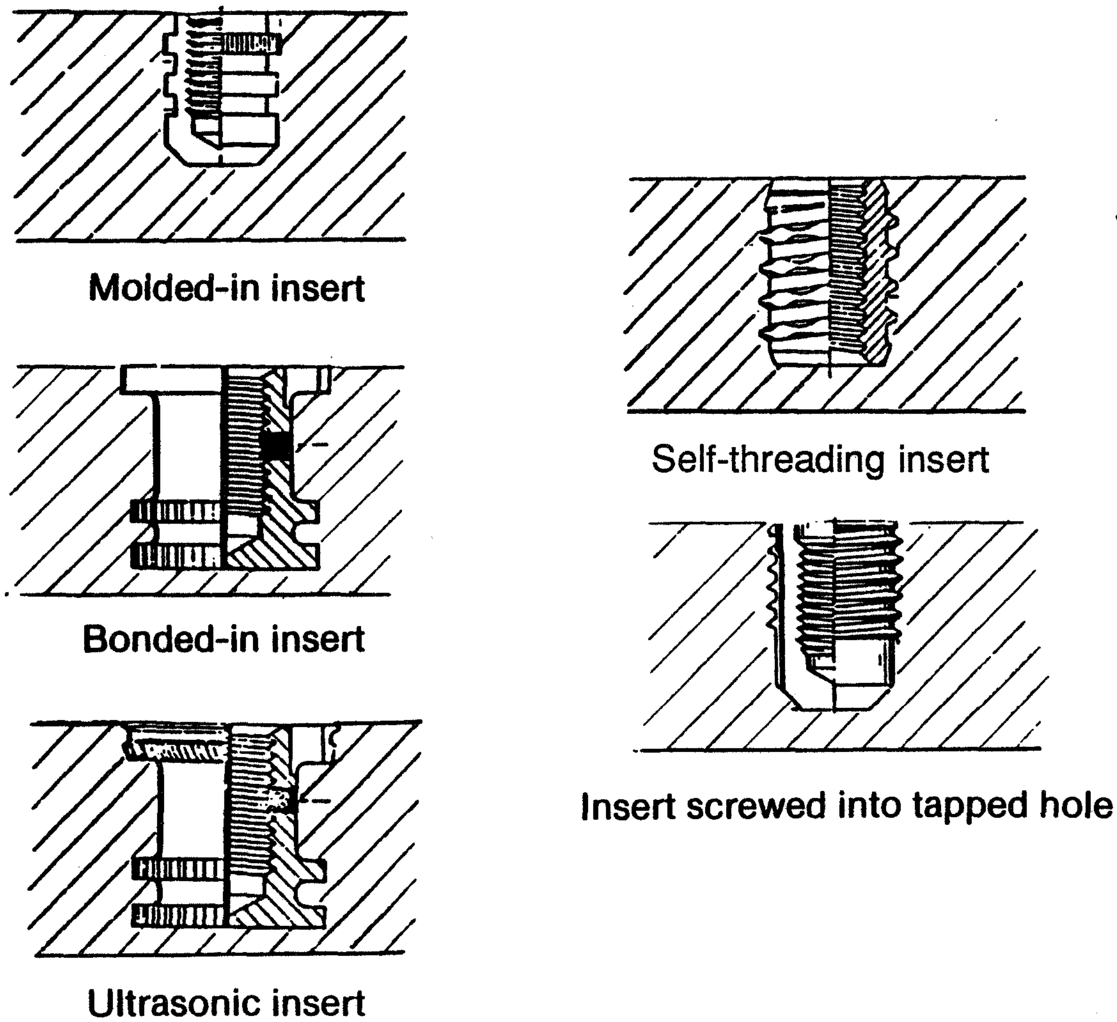

Figure 61. Concepts for Block Attachment Insert.

Fiber length	Inserts bonded-in	Pull-out (lbs)	Torque-out (in-lbs)
.125	No	3233	211
.125	Yes	4013	314
.25	Yes	3421	354
.50	Yes	4540	320

Figure 62. Insert Tests (1/4 - 28 Inserts).

5.4.4 Vane/Shroud Attachment

Although it had been decided to bond the composite Stage 1 vanes into the outer composite shrouds, the best method of achieving this goal remained to be determined. Consequently, three methods were investigated; these were: molding the vanes directly into the shrouds during the shroud molding cycle, bonding in straight-sided vanes, and bonding in vanes with dovetails. It also was very difficult to locate the vane properly in the shroud. It was found practical to bond in either straight-sided vanes or vanes with dovetails, and samples of both methods were fabricated. Frequency tests of these samples revealed that the vanes with the dovetail configuration had higher natural frequencies, and matched the analysis previously discussed (Section 5.4.2) much better than the straight-sided vanes. It was, therefore, decided to select this configuration for use in the composite F404 case/vane design.

To evaluate the pull-out capability of the selected vane configuration, several test specimens were constructed in which a composite Stage 1 vane was bonded into a disk made from graphite/PMR15 molding compound. Such a test specimen is shown in Figure 63, and the test results are shown in Figure 64. The different failure modes were the result of differences in disk support during the test. When the supports were adjacent to the vane, the vane failed; whereas, the disk failed when the supports were moved further from the vane. All test results were well in excess of any radial land that the vane would experience in service.

5.4.5 Flange Evaluation

One of the most critical areas in the design of a composite fan stator case are the flanges that attach the case to the rest of the engine structure. A series of tests, similar to those run for the F404 outer bypass duct, were conducted for flanges representing the F404 fan stator case. The results of these tests, illustrated in Figure 65, were utilized in the final design of the fan stator case.

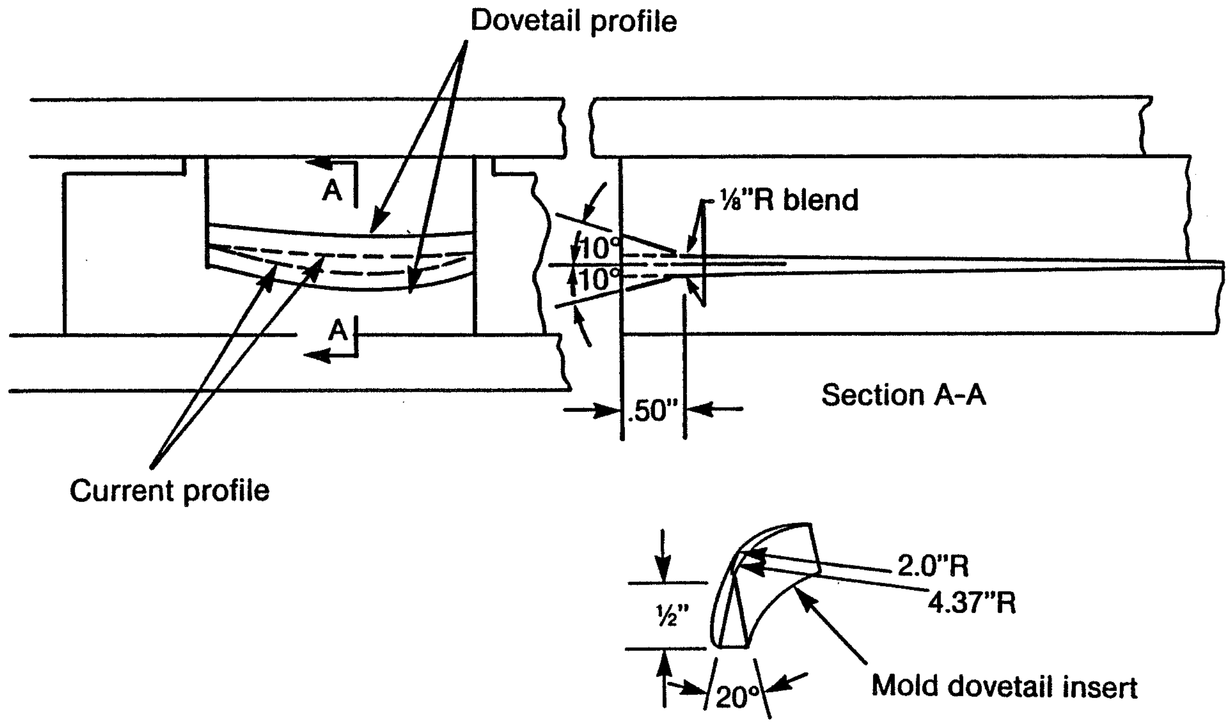

Figure 63. Vane Mold Tool with Dovetail and Dovetail Insert.

Specimen (No.)	Maximum load (lbs.)	Failure location
P17V13	3470	Disc fractured
P22X11	2250	Disc fractured
P29V9	4860	Vane

Figure 64. Test Results.

Flange	Test temperature	Design requirement	Test average
• Axial-static	RT	1425 lb/in	3220 lb/in
• Axial-fatigue*	RT	1425 lb/in	3320 lb/in
• Axial-static	480° F	1425 lb/in	2990 lb/in
• Axial-fatigue*	480° F	1425 lb/in	3050 lb/in
• Circumferential-static	RT	-1650 lb/in	-4100 lb/in
• Circumferential-fatigue	RT	-1650 lb/in	-4040 lb/in
• Circumferential-static	480° F	-1650 lb/in	-3630 lb/in
• Circumferential-fatigue	480° F	-1650 lb/in	-3540 lb/in

** Cycled 10,000 times to 1,425 lb/in (R = 0.1) before loading to failure; note, "-" is compression*

Figure 65. Stator Case Flange Testing.

It is apparent from these data that neither temperature nor fatigue loading has any significant effect on the flanges as designed for the fan stator case. Based on the results of these tests, it may be possible to reduce the flange thickness somewhat, but the effect on overall weight and cost was considered to be negligible and was not investigated further.

This testing concluded the fabrication and tests that were conducted in support of the design of the composite F404 fan case and vane assembly. The following sections deal with the overall design configuration, based on this effort.

5.5 Overall Configuration

Based on the data generated by the analyses and testing described in the preceding paragraphs, a number of overall structural configurations were evaluated for the composite version of the F404 stator case/vane assembly.

The first basic consideration was to determine if the stator case could be constructed as a continuous 360° structure, rather than having a horizontal split like the existing titanium case. The primary advantage of such an approach would be the elimination of the flange, thereby providing the ability to utilize a continuous belt of Kevlar for the containment system. The problems associated with assembly (primarily the installation of the Stage 2 rotor) and maintainability were such as to preclude this approach for this specific application.

Once the decision was made that the stator case must be split, as in the metal design, the problems of containment and stator vane installation were addressed. The solution of the containment design has already been discussed (Section 5.4.1); the remaining problems were the method of installation of the stator vane and how the vanes would be supported in the case. As stated in Section 5.4.2, the design approach incorporated composite Stage 1 vanes, but retained titanium vanes in Stages 2 and 3. Two basic installations methods considered were: stabbing the vanes through the case from the outside, and installing them from the inside without penetrating the casing. An examination of the machining problems and stress concentrations associated with stabbing the vanes through from the outside quickly eliminated this approach from further consideration, and all remaining effort was devoted to designs in which the vanes, or vane sectors, were installed from the inside.

From a casing design standpoint, the question now remained as to whether to make a stepped case, in which the case structure matched the flowpath over the rotors and stepped out to accept the vane shrouds, or a straight case which would have separate flowpath liners over the rotors. Preliminary analysis showed that a stepped case would require so much structure to meet the load and stiffness requirements that it would not be weight-competitive with a straight case. The study then came down to the question of how to best accomplish the attachment of the vanes and flowpath liners to the case.

The first concept that was studied (Figure 66) consisted of a series of flowpath liners over the rotor and a number of vane sectors, all of which were bolted to the casing by means of inserts in the liners and sectors and bolts which come through the casing from the outside. While this design was structurally adequate, the number of bolts required made the design too heavy, and the problems associated with installing the containment system over the bolt heads and still maintaining adequate containment capability made this an unfeasible approach.

The concept finally selected as the most promising approach is depicted, in Figure 67, as Configuration P01. Composite flowpath liners, made in approximately 90° sectors, are bonded to the casing. The appropriate ends of these liners are slotted, such that when the liners are all bonded in place, "T-slots" are formed which will accept the stator vane shrouds in a manner very similar to the existing metal design. This design requires that the outer shrouds of the titanium Stages 2 and 3 vanes be modified from the current configuration to move the tangs radially outward. This is necessary to provide enough composite material under the shroud tangs to withstand the vane loads under stall conditions.

This study also investigated the potential for utilizing unmodified Stage 2 and Stage 3 vanes. A configuration using the same approach as the P01 design is shown in Figure 68. Analysis revealed that the inner edges of the T-slots in the flowpath liners would break off under stall loads; to solve this problem, the P02 Configuration (shown in Figure 69) was developed. This configuration is similar to the P01 design, except that titanium vane-support liners have been attached to the flowpath liners to provide additional support in the slot area. Both the P01 and P02 designs utilized the existing inner shroud configuration for all stages.

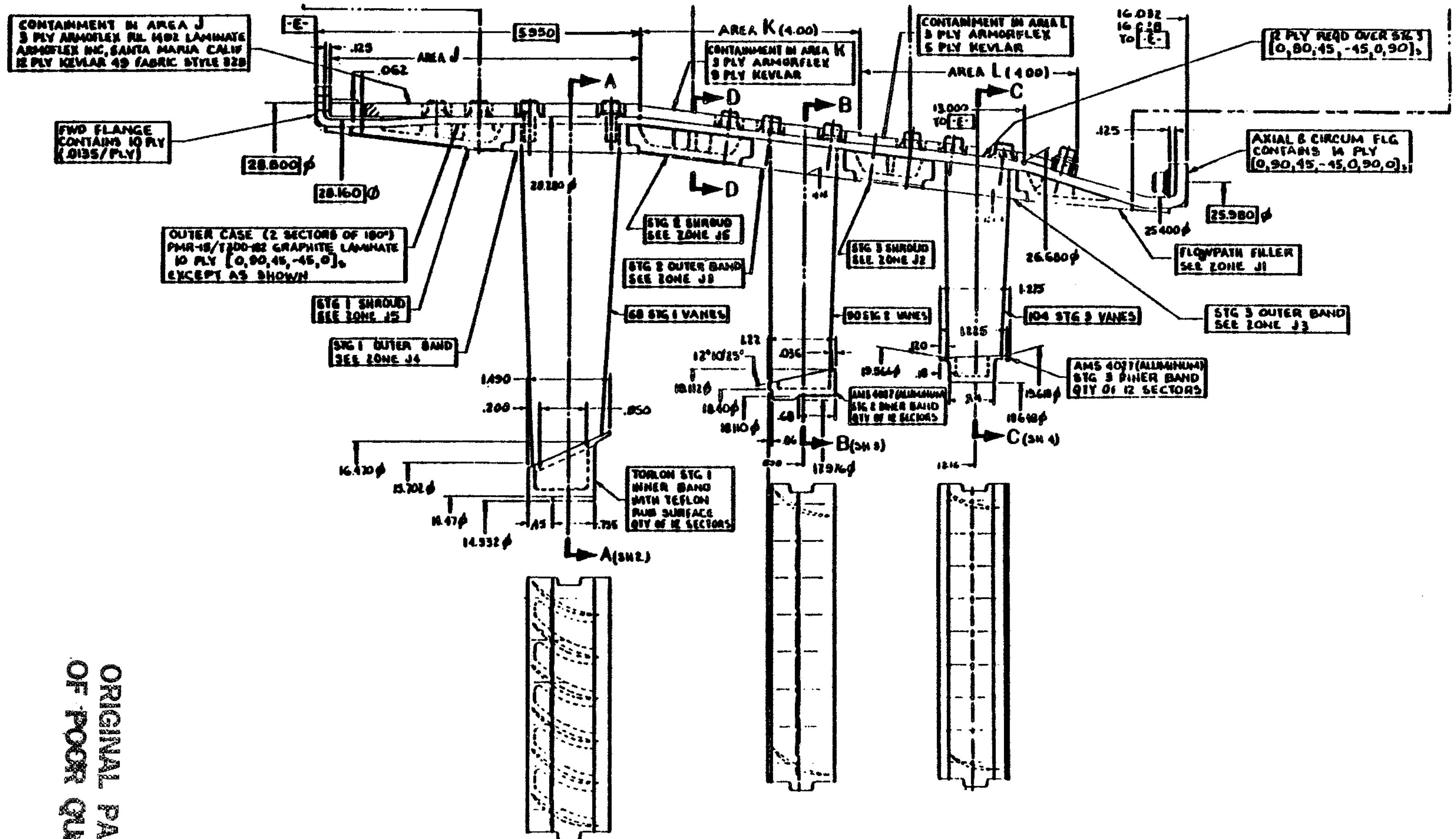

Figure 66. Composite Fan Case Configuration.

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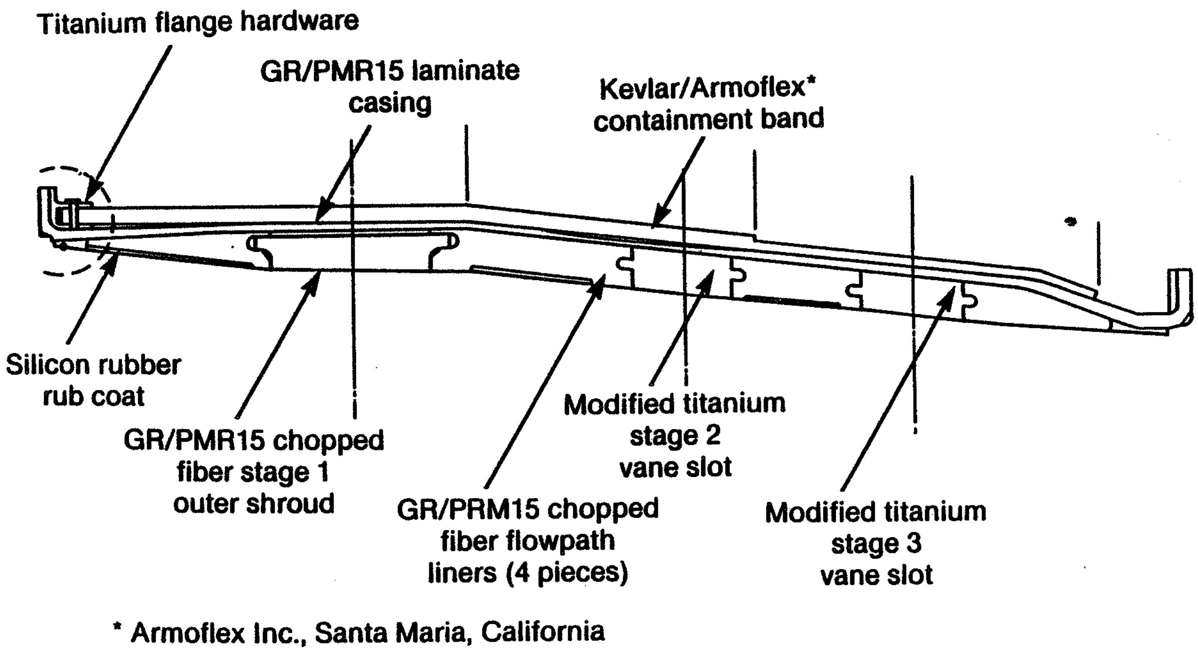

Figure 67. Composite Fan Case Cross Section (P01 Design).

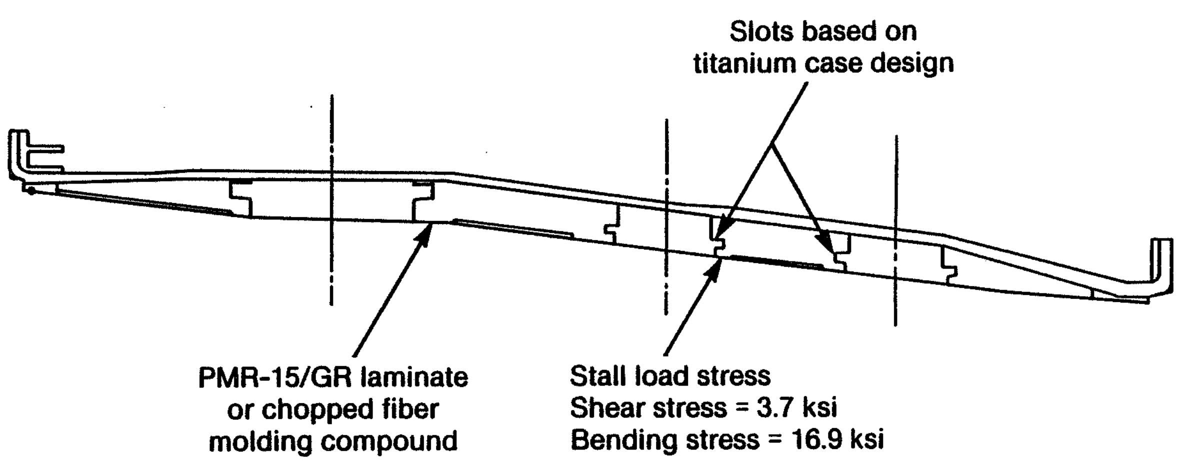

Figure 68. Composite Fan Case with Existing Stage 2 and Stage 3 Slot Areas.

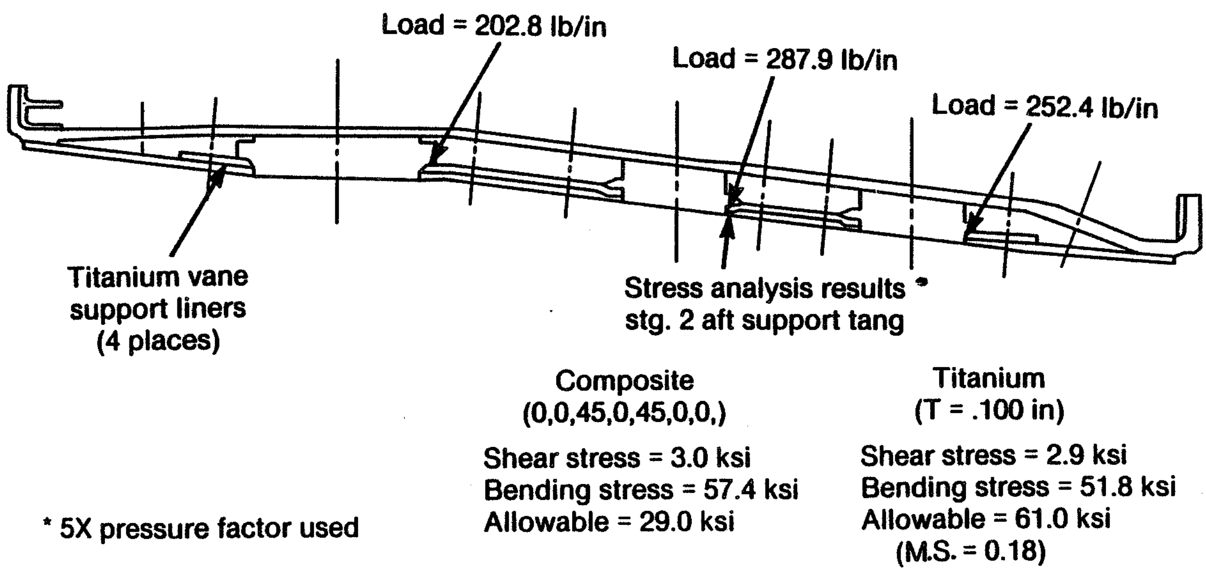

Figure 69. Titanium Vane Support Liners Stall Load Stress (5 × Pressure Factor Used), P02 Design.

In summary, the Configuration P01 design (Figure 67) was selected as the most promising composite approach to meeting the F404 fan stator assembly design requirements. However, if it is desired to construct a fan stator case that utilizes existing, unmodified, Stages 2 and 3 vanes, the P02 design, illustrated in Figure 69, should be implemented.

5.6 Weight Summary

One of the two major objectives of this study was to determine what potential for weight savings existed if a composite F404 stator case/vane assembly was substituted for the existing titanium structure. The baseline weight of the titanium assembly is 35.43 kg (78.1 lb); a breakdown of this weight is given in Figure 70. The weights of the two selected composite designs (P01 and P02) discussed in Section 5.5 were analytically determined. The P01 assembly weight was calculated at 30.44 kg (67.1 lb), which represents a 14.1% reduction from the titanium assembly weight. Figure 71 provides a weight breakdown of the P01 design. The P02 assembly weight was calculated at 32.75 kg (72.2 lb). The difference in weight between the P01 design and the P02 design is due primarily to the necessity of adding the titanium vane-support liners. This P02 weight represents only a 7.6% reduction from the baseline titanium weight. A breakdown of the P02 configuration weight is shown in Figure 72.

5.7 Cost Comparison

In addition to determining the potential for saving weight by using advanced composite materials in the F404 fan stator assembly, it was a major objective of the study to determine the effect this approach would have on the acquisition cost of the hardware. The cost analysis was performed only on the P01 design, since the P02 design would be used only to demonstrate

Component	Material	Weight
• Fan Casing	Titanium	42.42
• Vanes		
— Stage 1	Titanium	12.10
— Stage 2	Titanium	7.99
— Stage 3	Titanium	5.74
• Inner shrouds		
— Stage 1	Aluminum	3.34
— Stage 2	Aluminum	0.90
— Stage 3	Aluminum	1.05
• Misc. hardware	—	4.57
	Total weight	78.1

Figure 70. Titanium Fan Case Weight Summary.

Modified Titanium Stage 2 and 3 Vanes

Component	Material	Weight (lb)
• Case	— PRM-15/GR laminate	11.70
• Stg. 1 containment	— Kevlar/Armoflex	2.98
• Stg. 2 containment	— Kevlar/Armoflex	1.99
• Stg. 3 containment	— Kevlar/Armoflex	1.55
• Flange back-up hardware	— Titanium	5.80
• Outer shrouds and liners		
— Stg. 1 liner	— PMR-15/GR molding compound	3.63
— Stg. 1 outer shroud	— PMR-15/GR molding compound	3.28
— Stg. 2 liner	— PMR-15/GR molding compound	4.79
— Stg. 3 liner	— PMR-15/GR molding compound	3.48
— Aft liner	— PMR-15/GR molding compound	2.49
• Inner shrouds		
— Stg. 1	— PMR-15/GR molding compound	1.72
— Stg. 2	— Aluminum	0.90
— Stg. 3	— Aluminum	1.05
• Vanes		
— Stg. 1	— PMR-15/GR laminate	4.08
— Stg. 2	— Titanium	7.99
— Stg. 3	— Titanium	5.74
• Fasteners	— A-286	3.94
	Total assembly weight	67.1

(14.1% reduction)

Figure 71. Composite Fan Case Weight Summary, P01 Design.

Titanium Stage 2 and 3 Vanes and Titanium Vane Supports

Component	Material	Weight (lb)
• Case	— PMR-15/GR laminate	11.70
• Stg. 1 containment	— Kevlar/Armoflex	2.98
• Stg. 2 containment	— Kevlar/Armoflex	1.99
• Stg. 3 containment	— Kevlar/Armoflex	1.55
• Flange back-up hardware	— Titanium	5.80
• Outer shrouds and liners		
— Stg. 1 liner	— PMR-15/GR molding compound	3.63
— Stg. 1 outer shroud	— PMR-15/GR molding compound	3.28
— Stg. 2 liner	— PMR-15/GR molding compound	4.79
— Stg. 3 liner	— PMR-15/GR molding compound	3.48
— Aft liner	— PMR-15/GR molding compound	2.49
— Vane support liners	— Titanium	5.10
• Inner shrouds		
— Stg. 1	— PRM-15/GR molding compound	1.72
— Stg. 2	— Aluminum	0.90
— Stg. 3	— Aluminum	1.05
• Vanes		
— Stg. 1	— PMR-15/GR laminate	4.08
— Stg. 2	— Titanium	7.99
— Stg. 3	— Titanium	5.74
• Fasteners	— A-286	3.94
	Total assembly weight	72.2

(7.6% reduction)

Figure 72. Composite Fan Case Weight Summary, P02 Design.

the concept using unmodified Stage 2 and Stage 3 vanes. A cost comparison of the composite version versus the existing titanium baseline structure is shown in Figure 73. These numbers represent 250th unit costs and are in 1983 dollars.

	Composite	Titanium
• Fan case	22.0K	22.8K
• Shrouds	4.4K	4.3K
• Inner shroud	1.8K	
• 1st stage vanes	3.4K	4.0K
• Kevlar protection	3.1K	—
	34.7K	
• Add in stage 2 and 3 vanes	9.7K	9.7K
TOTAL	44.4K	40.8K

Figure 73. Cost Comparison.

Unlike the case of the F404 outer duct, where replacing the titanium structure with a composite structure resulted in a significant cost savings, the complexities of a composite fan case assembly resulted in a 10% cost increase. It is apparent that improvements in manufacturing methods will be required to make a composite version of the F404 fan stator assembly cost-competitive with the existing titanium structure. This is not to say, however, that composites would not be cost-competitive in other applications or when considering fan stator designs for new engines. There were many constraints put on the composite F404 fan stator assembly design by the necessity of matching existing configurations and requirements that would not be in effect in all-new designs.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Based on the work performed under this program, the following conclusions can be made:

1. The graphite/PMR15 material system is a viable material system and is suitable for application to major load-carrying engine structures.
2. When used as a replacement material for relatively simple titanium structures, such as the F404 outer bypass duct, significant cost and weight advantages can be obtained through the use of the graphite/PMR15 material system.
3. When utilized as a replacement material for more complex titanium structures, such as the F404 fan stator assembly, the restrictions imposed by an existing design may make the replacement of the titanium by the graphite/PMR15 material system not cost-effective.
4. If the graphite/PMR15 material is to be used in more complex structures (such as fan stator assemblies), it should be considered at the beginning of the design process so that the design can account for the characteristics of the material in the most advantageous way. If this is done, the composite design should be both lighter and less expensive than a comparable titanium design.
5. Although less weight-effective than the dry Kevlar cloth as a containment system, Armoflex is a viable, lightweight containment system if the containment material must be in close proximity to rotating blades.
6. Although impact testing was not done, from an aeroelastic standpoint, stator vanes can be constructed from graphite/PMR15 that are lighter than equivalent titanium vanes and have the same frequency response.

6.2 Recommendations

Based on the work accomplished on this program, the following recommendations are proposed to further develop the potential for the application of composite materials to major engine hardware:

1. The way the PMR15 matrix is made and applied to the reinforcement material should be reviewed to see what must be done to reduce the lot-to-lot and vendor-to-vendor variability.
2. Better high temperature adhesives should be developed that have more flow and higher ductility than the systems currently being utilized with graphite/PMR15 parts.
3. Work should be done to better understand the capability of the graphite/PMR15 system to withstand cyclic, short time exposures to temperatures above the inherent glass transition temperature of the material.

4. A high temperature, fiber-reinforced molding compound, using either thermoset or thermoplastic materials, should be developed that is capable of being utilized in the same temperature ranges as graphite/PMR15 laminates.

5. Inspection techniques are fairly well-defined to inspect parts in the factory, but work needs to be done to develop field inspection techniques.

6. Field repair techniques also need to be developed and demonstrated.

7.0 REFERENCES

1. Stotler, C.L. and Coppa, A.P., "Containment of Composite Fan Blades - Final Report," NASA CR-159544, July 1979.

2. Stotler, C.L., "Development of Advanced, Lightweight Containment Systems - Final Report," NASA CR-165212, May 1981.

APPENDIX A

REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED

PRE-IMPREGNATED WOVEN GRAPHITE FABRIC

1. SCOPE

1.1 Scope. This specification presents requirements for a pre-impregnated graphite fabric which utilizes a polyimide resin that yields useful properties up to temperatures of 600°F (316°C). The material is intended for preparation of graphite-resin reinforced composites for aircraft engine components.

1.1.1 Classification. This specification contains the following class:

CLASS A

1.2 Definitions. For purposes of this specification, the following definitions shall apply:

Purchaser - The procuring activity of the Aircraft Engine Group (AEG) of the General Electric Company that issued the procurement document invoking this specification.

Capability - The words "shall be capable of" or "capability test" indicate characteristics or properties required in the product but for which testing of each lot is not required. However, if such testing is performed by the Purchaser, material not conforming to the requirements shall be subject to rejection.

2. APPLICABLE DOCUMENTS

2.1 The following documents shall form a part of this specification to the extent specified herein. Unless a specific issue is specified, the latest revision shall apply.

AMERICAN SOCIETY FOR TESTING AND MATERIALS

ASTM D790 Flexural Properties of Plastics

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DWG TYPE

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES	SIGNATURES	MO. DA. YR
	DRAWN C. Lorentz	9/16/80
	CHECKED	9/16/80
	ENGRG	5.5/80
	MFG	
	MATL	
	ISSUED D. H. Tebbe	9/17/80

ALL SURFACES ✓
MATL:

GENERAL ELECTRIC
AIRCRAFT ENGINE GROUP CINCINNATI, OHIO, U.S.A.

SPECIFICATION FOR PMR-15
PRE-IMPREGNATED WOVEN GRAPHITE

SIZE	CODE IDENT NO.	
A	07482	4013240-802
SCALE	WT CALC ACTUAL	SHEET 1 of 15

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ASTM D1910	Construction Characteristics of Woven Fabrics
ASTM D2344	Apparent Horizontal Shear Strength of Reinforced Plastics by Short Beam Method
FEDERAL STANDARDS	
FTMS 406 Method 1011 Type I	Tensile Properties of Plastics
FED-STD-406	Plastics: Methods of Testing

GENERAL ELECTRIC SPECIFICATIONS

A50TF, 186CLA	Graphite Fabric

3. REQUIREMENTS

3.1 Raw Material

3.1.1 Graphite Fabric. The graphite fabric to be impregnated with polyimide resin shall conform to the requirements of A50TF186CLA. Except paragraph 1.1. Scope delete heat cleaned and paragraph 3.1.3 delete "182 style", also "which has been cleaned".

3.1.2 Polyimide Resin. The polyimide resin, when impregnated into the graphite fabric, shall produce the cured laminate mechanical properties required by this specification.

3.2 Physical Properties of the Uncrued Pre-impregnated Material

3.2.1 Material shall meet the requirements of Table I. (except delete width requirement.

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ENGRG [signature]	5/5/80
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TABLE I - PHYSICAL PROPERTIES OF UNCURED PRE-IMPREGNATED MATERIAL

PROPERTY	TEST METHOD (PARAGRAPH)	REQUIREMENT
Wet Resin Weight Percent	4.3.2	35-41%
Volatile Content,(1) Weight Percent	4.3.3	10 ± 3%
Weight(1)	4.3.4	1.05-1.33 lbs/yd^2 (0 kg/m^2)

(1) Capability

3.2.2 Incoming Material shall conform to HPLC signature at 5.3.

3.3 Shelf Life

3.3.1 The pre-impregnated material shall have the following minimum shelf life, from the date of manufacture, when stored in sealed moisture-proof containers:

(a) Six months below 0 degrees F (-18°C)
(b) Four months at 0 degrees F (-18C) to 40F (4 C)
(c) Three days at 60 to 80°F (15 to 27°C)

3.4 Properties of the Cured Laminate

3.4.1 Physical Properties

3.4.1.1 Each lot of material shall meet the laminate properties of Table II.

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CHECKED	[illegible]	9/16/80
ENGRG	[illegible]	5/5/80
MFG		
MATL		
ISSUED	[illegible]	9/17/80

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TABLE II - PROPERTIES OF THE CURED LAMINATE

PROPERTY	TEST METHOD (PARAGRAPH)	REQUIREMENT
Resin Content (1) Weight Percent	4.4.2.1	30±3
Fiber Content, (1) Volume Percent	4.4.2.2	61+4
Void Content, Volume Percent, Max	4.4.2.3	Three
Specific Gravity (2) Min	4.4.2.4	1.540
Thickness, Per Ply	4.4.2.5	.0125 to .0155 inch

(1) All values are for an average of four specimens, unless otherwise specified. No individual values shall be less than 90 percent of the value specified.

(2) Capability Test

3.4.2 Mechanical Properties

3.4.2.1 Each lot of material shall meet the cured laminate mechanical properties of Table III.

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TABLE III - MECHANICAL PROPERTIES OF THE CURED LAMINATE

PROPERTY	TEST METHOD (PARAGRAPH)	REQUIREMENT	
		Room Temperature	500°F
Tensile Strength, (2) Minimum	4.4.3.1	75,000 psi	70,000 psi
Tensile Modulus, (2) Minimum	4.4.3.1	8×10^6 psi	6×10^6 psi
Flexural Strength, (2)(3) Minimum	4.4.3.2	100,000 psi	90,000 psi
Flexural Modulus, (2)(3) Minimum	4.4.3.2	8×10^6 psi	7.5×10^6 psi
Short Beam Shear Strength, Minimum	4.4.3.3	6,000 psi	5,000 psi

(1) All values are for an average of four specimens, unless otherwise specified. No individual values shall be less than 90 percent of the value specified. All values shall be reported.
(2) All values are for tests run in the warp direction. The ratio of warp to fill properties is 1/.9.
(3) Capability

3.5 Certificate of Test

3.5.1 A certificate of test, in triplicate, on each shipment of material supplied to this specification shall be submitted by the manufacturer and mailed with or preceding the shipment of material. This certificate shall give the numerical results of all required tests and shall show that the results are in accordance with the requirements of this

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SIGNATURES		MO. DA. YR
DRAWN	C.Lorentz	9/16/80
CHECKED	[illegible]	2/16/81
ENGRG	[illegible]	5/5/80
MFG		
MATL		
ISSUED	D. H. Tedu. RW	9/17/80

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specification. The certificate shall also show the purchase order number, vendor's designation and lot number, quantity, and this specification number, CLASS, and revision number.

4. ~~QUALITY~~ ASSURANCE PROVISIONS

4.1 The Material vendor shall use the same ingredients and manufacturing processes for production material supplied to this specification as for approved sample material. If necessary to make any change in ingredients of processing. the vendor shall obtain permission from the Purchaser prior to incorporating such change.

4.3 Physical Properties of the Uncured Pre-impregnated Material

4.3.1 Physical properties of the uncured, pre-impregnated material shall be determined on samples which have been allowed a minimum of four hours to reach room temperature after removal from refrigeration.

4.3.2 Wet Resin Content. Duplicate samples, each weighing approximately 3 grams, shall be taken at random locations from each batch of pre-impregnated material and tested as follows:

(a) Weight samples to the nearest 0.0001 gram.
(b) Place the samples in separate 400 ml breakers and extract the polyimide resin with approximately 200 ml each of dimethylformamide by boiling for 5±1 minutes. (Time starts when the solvent starts to boil.)
(c) Cool the sample. Decant the solvent (dimethylformamide) and wash the samples twice with acetone.
(d) Place the samples in a tared aluminum foil pan and dry in an air circulating oven at 375°F±5 for 10±5 minutes.
(e) Remove the specimens from the oven and cool to room temperature in a desiccator.
(f) Reweigh the samples to the nearest 0.0001 gram (W_2).
(g) Percent resin solids, measured to the nearest 0.1 percent, shall be calculated as follows:

$$\text{Percent Resin Solids} \quad (1 - \frac{W_2}{W_1}) \times 100$$

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MATL:

SIGNATURES	MO. DA. YR
DRAWN C. Lorentz	9/16/80
CHECKED [illegible]	9/16/80
ENGRG [illegible]	5/5/80
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MATL	
ISSUED D H Teeker Kw	9/1/80

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(h) Calculate the arithmetic mean of the two determinations as the resin solids content of the sample. Report both individual results and the arithmetic mean.

4.3.3 Volatile Content. Samples, approximately 4 x 4 inches (51 x 51mm), shall be taken from the end of a roll of pre-impregnated material and tested as follows:

(a) Weight duplicate samples into tared aluminum dishes to the nearest 0.001 gram. Sample must lay flat and shall be no more than one ply in thickness. (W_1)
(b) Place the samples in an air circulating oven maintained at 450 F$\pm$5 for 20$\pm$0.5 minutes.
(c) Remove the samples from the oven, cool to room temperature in a desiccator and reweigh to the nearest 0.001 gram (W_2).
(d) Volatile content, measured to the nearest 0.1 percent, shall be calculated as follows:

$$\text{Percent Volatile Content} = \frac{W_1 - W_2}{W_1} \times 100$$

(e) Calculate the arithmetic mean of the two determinations as the total volatile content of the sample. Report both individual results and the arithmetic mean.

4.3.4 Weight. Weight shall be determined per ASTM D1910, Method 39.

4.4 Properties of the Cured Laminate

4.4.1 Laminate Fabrication

4.4.1.1 The laminate panel shall consist of 8 plies, impregnated with the resin system required by the specification, to produce a cured laminate of .100 to .124 inch thickness. The layup when cured per 4.4.1.1.1 shall provide the minimum room temperature mechanical properties as indicated in Table III.

4.4.1.1.1 Layup and Cure Cycle. Cut 8 plies of pre-impregnated material to produce the cured laminate and process as follows:

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DWG TYPE

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES	SIGNATURES	MO. DA. YR
	DRAWN C. Lorentz	9/16/80
	CHECKED [illegible]	2/16/82
	ENGRG [illegible]	5/5/82
	MFG	
ALL SURFACES ✓	MATL	
MATL:	ISSUED D H Tebar Rw	7/17/80

GENERAL ELECTRIC
AIRCRAFT ENGINE GROUP CINCINNATI, OHIO, U.S.A.

SPECIFICATION FOR PMR-15
PRE-IMPREGNATED WOVEN GRAPHITE

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The laminate is to be cured in a vacuum bag autoclave (or simulated using vacuum bag in press) as follows:

Stack eight (8) plies of prepreg on a teflon released pressure plate. Place one (1) ply of one (1) mil thick porous Release Ease (or equivalent) and five (5) plies of 7781 glass bleeder on the stack. Bag with Kapton and high temperature bag sealant. Apply 3-5 inches Hg vacuum. Raise temperature at 3-5°F per minute to 180±5°F and hold 55-65 minutes. Raise temperature at 3-5°F per minute to 400±5°F and hold for 40-50 minutes. After hold period, apply full vacuum pressure and heat to 570-580°F at 3-5°F per minute. At 445-455°F add 145-155 psi autoclave pressure. Hold 575°F, 150 psi autoclave and full vacuum for 180-190 minutes. Cool slowly under pressure. Post cure per manufacturers recommendation. (Normally 10 to 24 hours at 600°F)

4.4.2 Physical Properties

4.4.2.1 Resin Content. Samples, weighing from one to two grams, taken from the cured laminate, which are representative of each lot shall be tested as follows:

(a) Dry the sample for a minimum of one hour at 300°F±10 (149°C±6).
(b) Cool in a desiccator to room temperature and weigh sample to the nearest 0.001 gram (W_1).
(c) Place sample in a 250 cm^3 Eilenmeyer flask equipped with ground glass joints and add 20 cm^3 of sulfuric acid, 1.84 specific gravity, and heat under condensers until fuming.
(d) Digest until the composite is visibly disintegrated and resin and fiber particles are dispersed throughout the solution.
(e) Transfer to a convenient size beaker and add 30 percent hydrogen peroxide dropwise until the solution is water white.
(f) At this point add two more cm^3 of 30 percent hydrogen peroxide to the solution and fume the acid solution for an additional ten minutes to ensure complete decomposition of the polymer.
(g) Cool the mixture to 75°F±5 (24°C±3).

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ALL SURFACES ✓
MATL:

SIGNATURES		MO-DA-YR
DRAWN	C. Lorentz	9/16/80
CHECKED	[illegible]	2/16/8[illegible]
ENGRG	[illegible]	5/5/8[illegible]
MFG		
MATL		
ISSUED	[illegible]	9/17/80

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SPECIFICATION FOR PMR-15
PRE-IMPREGNATED WOVEN GRAPHITE

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(h) Collect the fibers by vacuum filtration through a medium porosity-sintered glass crucible that has been weighed to the nearest 0.001 gram (W_2).

(i) After the sulfuric acid has been filtered off, wash the fibers in the crucible thoroughly with 600 cm^3 of distilled water, added a few cm^3 at a time. Rinse with acetone to remove all moisture.

(j) Remove the crucible from the filtering system and place in an open beaker.

(k) Dry fibers for a minimum of 45 minutes at 325°F$\pm$10 (163°C$\pm$6), cool in a desiccator, and weigh to the nearest 0.001 gram (W_3).

(l) Resin content, measured to the nearest 0.1 percent, shall be calculated as follows:

$$\text{Percent Resin Content} = \frac{W_1 - (W_2 - W_3)}{W_1} \times 100$$

4.4.2.2 Fiber Content. Fiber content of the cured laminate shall be calculated as follows:

$$\frac{\text{Percent Resin Content (Weight fraction of resin)}}{\text{Specific gravity of resin}} +$$

$$\frac{\text{Percent Fiber Content (Weight fraction of fiber)}}{\text{Specific gravity of fiber}} =$$

Total volume of cured laminate sample

$$\text{Percent volume of fiber} = \frac{\text{Volume of fiber}}{\text{Total volume}} \times 100$$

EXAMPLE: Resin content of cured laminate sample = 30%.
Therefore: Fiber content = 70%.

$$\frac{30}{1.308} + \frac{70}{1.76} = 22.94 + 39.77 = 62.71 \text{ Total Volume}$$

$$\text{Percent Fiber Volume} = \frac{39.77}{62.71} \times 100 = 63.4$$

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MATL:

SIGNATURES		MO-DA-YR
DRAWN	C. Lorentz	9/16/80
CHECKED	[illegible]	[illegible]
ENGRG	[illegible]	5/5/80
MFG		
MATL		
ISSUED	D H Teber Rw	9/17/80

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NOTE: The density of the appropriate lots of fiber and resin utilized in the laminate shall be determined from certifications and test results received.

4.4.2.3 Void Content. Void content of the cured laminate shall be calculated as follows:

$$\text{Void Content, Volume Percent} = 100 - pL \left(\frac{R}{pr} + \frac{F}{pf}\right)$$

Where: p_L = density of the laminate determined using, FED-STD-406, Method 5011, g/cm^3
R = resin content from 3.4.1.1, weight percent
F = fiber content (100-R), weight percent
pr = density of the resin used in the laminate, from the appropriate certifications and test results
pf = density of the fiber used in the laminate, from the appropriate certifications and test results

4.4.2.4 Specific Gravity. Specific gravity shall be determined per FED-STD-406, Method 5011.

4.4.2.5 Thickness. Thickness of cured laminate per ply shall be determined by measuring the thickness of the laminate at five random locations to the nearest .0001 inch (0.0025 mm). The readings are averaged and divided by the number of plies; this value is the cured laminate thickness per ply.

4.4.3 Mechanical Properties

4.4.3.1 Tensile Strength and Modulus. Tensile strength and modulus shall be determined per FTMS 406 Method 1011 Type 1.

4.4.3.2 Flexural Strength and Modulus. Flexural strength and modulus shall be determined per ASTM D790 Method I with the following exceptions or additions.

4.4.3.2.1 Specimen Description. Unless otherwise specified by the Purchaser, the test specimen shall be as shown in Figure 2. Fibers are aligned parallel to the longitudinal

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MATL:

SIGNATURES	MO-DA-YR
DRAWN C. Lorentz	9/16/80
CHECKED	9/16/80
ENGRG	5/5/80
MFG	
MATL	
ISSUED	7/17/80

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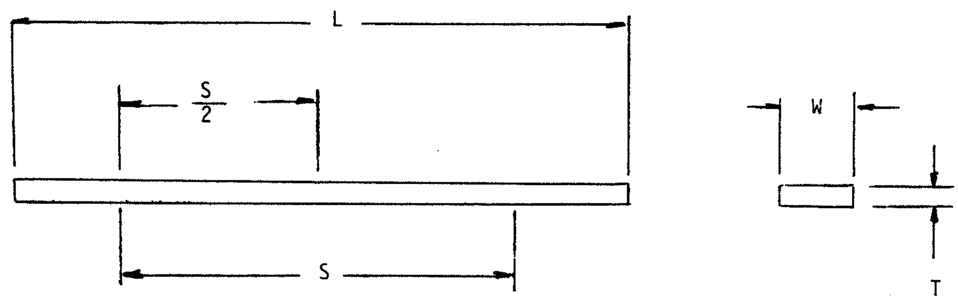
axis and the width and thickness of the specimen shall be measured with a .157 inch (4.00 mm) radius dual face ball anvil micrometer.



1. Specimen configuration is as shown above. Fibers are aligned parallel to the longitudinal axis.

2. Specimen dimensions:

   Length (L) = 5.00 ± .03 inches (101.60±3.05 mm)
   Width (W) = .500±.010 inches (12.700±0.254 mm)
   Thickness (T) = .100 to .124 (8 plies)

Figure 2 - Flexural Strength and Modulus Specimen

4.4.3.2.2 Test Conditions. Unless otherwise specified by the Purchaser, the specimen shall be tested to failure under three point flexure over a 32:1±15 percent span-to-depth ratio using nominal .125 inch (3.18 mm) radius steel rods for load and reaction supports. Specimen shall be loaded to failure in a universal testing machine capable of recording specimen deflection at a load rate of .05 inches (1.27 mm) per minute.

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4.4.3.2.3 Calculations. The flexural strength and modulus shall be calculated from the following formulae:

Flexural Strength (S)

U.S. Units $\quad lbs/in^2 = \frac{3PL}{2\ bd^2}$

SI Units $\quad (MPa) = \frac{3PL}{2\ bd^2} \times 10^6$

Where: P = ultimate failure load in pounds (MN) to the nearest pound (MN)
L = span length in inches (mm) to the nearest .005 inch (0.13 mm)
b = specimen width in inches (mm) to the nearest .001 inch (0.025 mm)
d = specimen thickness in inches (mm) to the nearest .0005 inch (0.013 mm)

Flexural Modulus (E_B)

U.S. Units $\quad lbs/in^2 = \frac{L^3M}{4\ bd^3}$

SI Units $\quad MPa = \frac{L^3M^c}{4\ bd^3}$

Where: L = span length in inches (mm) to the nearest .005 inch (0.13 mm)
M = initial slope of the load-deflection curve in inches (m) as measured by deflectometer to the nearest .0001 inch (0.0025 mm)
b = specimen width in inches (mm) to the nearest .001 inch (0.025 mm)
d = specimen thickness in inches (mm) to the nearest .0005 inch (0.013 mm)

NOTE: In calculating the flexural modulus in SI units, all millimeter values should be converted to the appropriate value in meters in order to make the expression dimensionally correct.

4.4.3.3 Short Beam Shear Strength. Short beam shear strength shall be determined per ASTM D2344 with the following exceptions and additions.

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MATL:

SIGNATURES	MO-DA-YR
DRAWN C. Lorentz	9/16/80
CHECKED [signature]	9/16/80
ENGRG [signature]	5/5/80
MFG	
MATL	
ISSUED [signature]	

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4.4.3.3.1 Specimen Description. Unless otherwise specified by the Purchaser, the test specimen shall be fabricated to the following dimensions:

Length (L) = 2.00±.015
Width (W) = 0.50±.01
Thickness (T) = .100 to .124 (8 plies)
Load Rate .05 in/min.

NOTE: Width and thickness of specimen shall be measured using a .157 inch (4.00 mm) radius dual face ball anvil micrometer.

4.4.3.3.2 Test Conditions. Unless otherwise specified by the Purchaser, the specimen shall be loaded to failure using a .125 inch (3.18 mm) radius steel rod as the loading nose. When testing at temperatures other than ambient, specimens shall be held for 10+1, -0 minutes at the test temperature prior to testing.

4.4.3.3.3 Calculations. The short beam shear strength shall be calculated from the following formula:

Short Beam Shear Strength (S)

U.S. Units lbs/in^2 $= \frac{3P}{4Wt}$

SI Units (MPa) $= \frac{3P}{(4Wt)} \times 10^3$

Where: P = ultimate failure load in pounds (MN) to the nearest pound (MN)
W = specimens width in inches (mm) to the nearest .001 inch (0.025 mm)
t = specimen thickness in inches (mm) to the nearest .0005 inch (0.013 mm)

5. PREPARATION FOR DELIVERY

5.1 Packing

5.1.1 Unless otherwise specified, tape shall be wound on spools of not less than six inches (152 mm) diameter and interleaved with a contrasting color separator film. Tape

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ALL SURFACES ✓
MATL:

SIGNATURES		MO-DA-YR
DRAWN	C. Lorentz	9/16/80
CHECKED	[illegible]	9/16/80
ENGRG	[illegible]	[illegible]
MFG		
MATL		
ISSUED	[illegible]	[illegible]

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ends shall be secured. Each spool of pre-impregnated material shall be wrapped individually in a material which will ensure protection from damage that may result from handling, shipping and storage.

5.2 Marking

5.2.1 The following information shall be included on the exterior of each shipping container and on a label located on each spool of material:

(a) Purchase order number
(b) Manufacturer's name
(c) Date of manufacture
(d) Lot number
(e) Spool number and length
(f) Specification number, CLASS, and revision number

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DWG TYPE

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES

ALL SURFACES ✓
MATL:

SIGNATURES	MO. DA. YR
DRAWN C. Lorentz	9/16/80
CHECKED [illegible]	[illegible]
ENGRG [illegible]	[illegible]
MFG	
MATL	
ISSUED [illegible]	[illegible]

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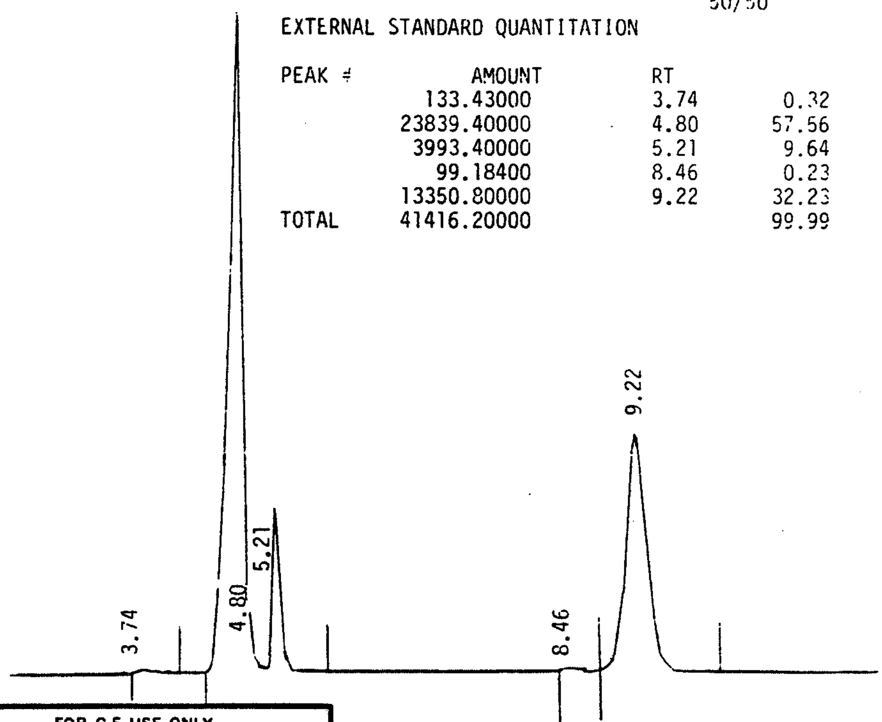
Aug. 12, 1980 15:21:30 Chart 2.00 CM/MIN Flow 1.00 ML/MIN
PRESSURE 4100.0 DETECTOR 254/050
SAMPLE #9 RUN #11 CALC #0
COLUMN 3 X 60A° μ PORASIL SOLVENT MeOH/H_2O 50/50 OPR ID: 10

EXTERNAL STANDARD QUANTITATION

PEAK #	AMOUNT	RT	
	133.43000	3.74	0.32
	23839.40000	4.80	57.56
	3993.40000	5.21	9.64
	99.18400	8.46	0.23
	13350.80000	9.22	32.23
TOTAL	41416.20000		99.99



5.3 STANDARD
HPLC SIGNATURE - PMR15

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ALL SURFACES ✓
MATL:

SIGNATURES		MO. DA. YR
DRAWN	C. Lorentz	9/16/80
CHECKED	R. Pratt	9/16/80
ENGRG	R. Pratt	9/16/80
MFG		
MATL		
ISSUED		

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PRE-IMPREGNATED WOVEN FIBERGLASS FABRIC

SCOPE

1.1 Scope. This specification presents requirements for a pre-impregnated fiberglass fabric which utilizes a polyimide resin that yields useful properties up to temperatures of 600°F (316°C). The material is intended for preparation of fiberglass-resin reinforced composites for aircraft engine components.

1.1.1 Classification. This specification contains the following class:

CLASS A: Impregnated 181 Style Glass Cloth
CLASS B: Impregnated 120 Style Glass Cloth

1.2 Definitions. For purposes of this specification, the following definitions shall apply:

Purchaser - The procuring activity of the Aircraft Engine Group (AEG) of the General Electric Company that issued the procurement document invoking this specification.

Capability - The words "shall be capable of" or "capability test" indicate characteristics or properties required in the product but for which testing of each lot is not required. However, if such testing is performed by the Purchaser, material not conforming to the requirements shall be subject to rejection.

2. APPLICABLE DOCUMENTS

2.1 The following documents shall form a part of this specification to the extent specified herein. Unless a specific issue is specified, the latest revision shall apply.

MILITARY SPECIFICATION

MIL-C-9084 Cloth, Glass Finished for Polyester Laminates
MIL-Y-1140 Yarn, Cord, Sleeving, Cloth, and Tape-Glass

AMERICAN SOCIETY FOR TESTING AND MATERIALS

ASTM D790	Flexural Properties of Plastics
ASTM D1910	Construction Characteristics of Woven Fabrics
ASTM D2344	Apparent Horizontal Shear Strength of Reinforced Plastics by Short Beam Method.

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON	SIGNATURES	DAY	MO	YR	GENERAL ELECTRIC
FRACTIONS DECIMALS ANGLES	DRAWN				
	CHECKED	12	13	80	
	ISSUED	18	12	80	SPECIFICATION FOR PMR-15 PRE-IMPREGNATED WOVEN FIBERGLASS FABRIC
	ENGRG				
ALL SURFACES ✓	MFG				
MATL	MATL	18	13	80	

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FEDERAL STANDARDS

FED-STD-406 Plastics: Methods of Testing

3. REQUIREMENTS

3.1 General Requirements

3.1.1 Glass Fabric. The glass fabrics shall be clean, evenly woven, and shall conform to the quality requirements of MIL-C-9084, MIL-Y-1140 and to the requirements shown below:

CLASS A: Style 7781, Finish A1100
CLASS B: Style 120, Finish A1100

3.2 Physical Properties of the Uncured Pre-impregnated Material

3.2.1 Material shall meet the reuirements of Table I for Class A material and Table II for Class B material.

TABLE I - PHYSICAL PROPERTIES OF UNCURED CLASS A PRE-IMPREGNATED MATERIAL

PROPERTY	TEST METHOD (PARAGRAPH)	REQUIREMENT
Wet Resin Content Weight Percent	4.3.2	45 ± 3%
Volatile Content, (1) Weight Percent	4.3.3	9 ± 3%

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON: FRACTIONS DECIMALS ANGLES ± ± ±
ALL SURFACES ✓
MATL

SIGNATURES	DAY	MO	YR
DRAWN	10		
CHECKED	12	13	80
ISSUED	18	2	80
ENGRG			
MFG			
MATLS	12	13	80

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TABLE II - PHYSICAL PROPERTIES OF UNCURED CLASS B PRE-IMPREGNATED MATERIAL

PROPERTY	TEST METHOD (PARAGRAPH)	REQUIREMENT
Wet Resin Content	4.3.2	56 $\pm$ 4
Volatile Content,(1) Weight Percent	4.3.3	12 $\pm$ 3.

(1) Capability

3.2.2 Incoming material shall conform to HPLC signature per 5.3.

3.3 Shelf Life

3.3.1 The pre-impregnated material shall have the following minimum shelf life, from the date of manufacture, when stored in sealed moisture-proof containers:

(a) Six months below -18°C (0°F)
(b) Four months at -18 to 4°C (0 to 40°F)
(c) Three days at 15 to 27°C (60 to 80°F)

3.4 Properties of the Cured Laminate

3.4.1 Physical Properties

3.4.1.1 Each lot of material shall meet the laminate properties of Table III for Class A and Class B material.

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON:
FRACTIONS DECIMALS ANGLES
ALL SURFACES ✓
MATL

SIGNATURES	DAY	MO	YR
DRAWN			
CHECKED E. Lorenz	12	13	80
ISSUED H B Meyer	18	12	80
ENGRG			
MFG			
MATL [signature]	12	13	80

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SPECIFICATION FOR PMR-15 PRE-IMPREGNATED WOVEN FIBERGLASS FABRIC

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TABLE III - PORPERTIES OF THE CURED LAMINATE

PROPERTY	TEST METHOD (PARAGRAPH)	REQUIREMENT
Resin Content (1) Weight Percent	4.4.2.1	33 ± 3
Fiber Content (1) Volume Percent	4.4.2.2	60 ± 4
Void Content, Volume Percent, Max	4.4.2.3	Three
Specific Gravity (2) Min	4.4.2.4	1.92 ± .02
Thickness, Per Ply - Class A Class B	4.4.2.5	.008 ± .001" .004 ± .0005"

(1) All values are for an average of four specimens, unless otherwise specified.
(2) Capability Test

3.4.2 Mechanical Properties

3.4.2.1 Each lot of material shall meet the cured laminate mechanical properties of Table IV for Class A material and Table V for Class B material.

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON: FRACTIONS DECIMALS ANGLES

ALL SURFACES ✓

MATL

SIGNATURES	DAY	MO	YR
DRAWN			
CHECKED	12	13	80
ISSUED	18	12	80
ENGRG			
MFG			
MATL	12	15	80

GENERAL ELECTRIC

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SPECIFICATION FOR PMR-15 PRE-IMPREGNATED WOVEN FIBERGLASS FABRIC

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TABLE IV - MECHANICAL PROPERTIES OF THE CURED LAMINATE FOR CLASS A MATERIAL

PROPERTY	TEST METHOD (PARAGRAPH	REQUIREMENT Room Temperature	500°F
Tensile Strength, (2) Ultimate	4.4.3.1	70,000 psi	55,000 psi
Tensile Modulus, (2) Minimum	4.4.3.1	3.0×10^6	2.6×10^6
Flexural Strength, (2)(3) Ultimate	4.4.3.2	90,000 psi	64,000 psi
Flexural Modulus, (2)(3) Minimum	4.4.3.2	3.3×10^6	3.0×10^6
Short Beam Shear Strength, Minimum	4.4.3.3	8,500 psi	4,500 psi

TABLE V - MECHANICAL PROPERTIES OF THE CURED LAMINATE FOR CLASS B MATERIAL

PROPERTY	TEST METHOD (PARAGRAPH)	REQUIREMENT Room Temperature	500 F
Tensile Strength, (2) Ultimate	4.4.3.1	60,000 psi	50,000 psi
Tensile Modulus, (2) Minimum	4.4.3.1	3.0×10^6	2.6×10^6
Flexural Strength, (2)(3) Ultimate	4.4.3.2	80,000 psi	60,000 psi
Flexural Modulus, (2)(3) Minimum	4.4.3.2	3.0×10^6	2.6×10^6
Short Beam Shear Strength, Minimum	4.4.3.3	7,000 psi	4,500 psi

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON
FRACTIONS DECIMALS ANGLES
ALL SURFACES ✓
MATL

SIGNATURES	DAY	MO	YR
DRAWN	[illegible]	[illegible]	[illegible]
CHECKED C. Laient	12	13	80
ISSUED H. Meyer	18	2	80
ENGRG			
MFG			
MATL [illegible]	12	13	80

GENERAL ELECTRIC

SPECIFICATION FOR PMR-15 PRE-IMPREGNATED WOVEN FIBERGLASS FABRIC

SIZE A | CODE IDENT NO. 07482 | 4013240-871
SCALE | SHEET 5 of 13
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LTR	DESCRIPTION	DATE	APPROVED

(1) All values are for an average of four specimens, unless otherwise specified. No individual values shall be less than 90 percent of the value specified. All values shall be reported.

(2) All values are for tests run in the warp direction.
(3) Capability.

3.5 Certificate of Test

3.5.1 A certificate of test, in triplicate, on each shipment of material supplied to this specification shall be submitted by the manufacturer and mailed with or preceding the shipment of material. This certificate shall give the numerical results of all required tests and shall show that the results are in accordance with the requirements of this specification. The certificate shall also show the purchase order number, vendor's designation and lot number, quantity, and this specification number, CLASS, and revision number.

4. QUALITY ASSURANCE PROVISIONS

4.1 The Material vendor shall use the same ingredients and manufacturing processes for production material supplied to this specification as for approved sample material. If necessary to make any change in ingredients of processing, the vendor shall obtain permission from the Purchaser prior to incorporating such change.

4.3 Physical Properties of the Uncured Pre-impregnated Material

4.3.1 Physical properties of the uncured, pre-impregnated material shall be determined on samples which have been allowed a minimum of four hours to reach room temperature after removal from refrigeration.

4.3.2 Wet Resin Content. Duplicate samples, each weighing approximately 3 grams, shall be taken at random locations from each batch of pre-impregnated material and tested as follows:

(a) Weigh samples to the nearest 0.0001 gram.
(b) Place the samples in separate 400 ml breakers and extract the polyimide resin with approximately 200 ml each of dimethylformamide by boiling for 5 ± 1 minutes (time starts when the solvent starts to boil).
(c) Cool the sample. Decant the solvent (dimenthylformamide) and wash the samples twice with acetone.
(d) Place the samples in a tared aluminum foil pan and dry in an air-circulating oven at 375°F ± 5 for 10±5 minutes.
(e) Remove the specimens from the oven and cool to room temperature in a desiccator.
(f) Reweigh the samples to the nearest 0.0001 gram (W_2)
(g) Percent resin solids, measured to the nearest 0.1 percent, shall be calculated

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON: FRACTIONS DECIMALS ANGLES	SIGNATURES	DAY	MO	YR	GENERAL ELECTRIC
	DRAWN				
	CHECKED C. Lanza	12	13	80	SPECIFICATION FOR PMR-15 PRE-IMPREGNATED WOVEN FIBERGLASS FABRIC
	ISSUED	18	12	80	
ALL SURFACES ✓	ENGRG				
MATL	MFG				
	MATL	12	13	80	SIZE A · CODE IDENT NO. 07482 · 4013240-871
					SCALE · SHEET 6 of 13

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LTR	DESCRIPTION	DATE	APPROVED

as follows:

$$\text{Percent Resin Solids } (1 - \frac{W_2}{W_1}) \times 100$$

(h) Calculate the arithmetic mean of the two determinations as the resin solids content of the sample. Report both individual results and the arithmetic mean.

4.3.3 Volatile Content. Samples, approximately 4 X 4 inches (51 X 51mm), shall be taken from the end of a roll of pre-impregnated material and tested as follows:

(a) Weight duplicate samples into tared aluminum dishes to the nearest 0.0001 gram. Sample must lay flat and shall be no more than one ply in thickness. (W_1)

(b) Place the samples in an air-circulating oven maintained at 450°F $\pm$5 for 20 $\pm$ 0.5 minutes.

(c) Remove the samples from the oven, cool to room temperature in a disiccator and reweigh to the nearest 0.0001 gram (w_2).

(d) Volatile content, measured to the nearest 0.1 percent, shall be calculated as follows:

$$\text{Percent Volatile Content} = \frac{W_1 - W_2}{W_1} \times 100$$

(e) Calculate the arithmetic mean of the two determinations as the total volatile content of the sample. Report both individual results and the arithmentic mean.

4.3.4 Weight. Weight shall be determined per ASTM D1910, Method 39.

4.4 Properties of the Cured Laminate

4.4.1 Laminate Fabrication

4.4.1.1 The laminate panel shall consist of 14 plies of Class A material, or 25 plies of Class B material required by the specification, to produce a cured laminate of .100 to .124 inch thickness. The layup when cured per 4.4.1.1 shall provide the minimum room temperature mechanical properties as indicated in Table IV for Class A material and Table V for Class B material.

4.4.1.2 Layup and Cure Cycle. Cut 14 plies of pre-impregnated material per par. 4.4.1.1 to produce the cured laminate and process as follows:

The laminate is to be cured in a vacuum bag autoclave (or simulated using vacuum bag in press) as follows:

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON	SIGNATURES	DAY	MO	YR	GENERAL ELECTRIC
FRACTIONS DECIMALS ANGLES	DRAWN				DEPT LOC
ALL SURFACES ✓	CHECKED C. Lowrey	12	15	80	SPECIFICATION FOR PMR-15 PRE-IMPREGNATED WOVEN FIBERGLASS FABRIC
MATL	ISSUED / ENGR	18	12	80	
	MFG				
	MATL E Hansen	12	13	80	SIZE A · CODE IDENT NO. 07482 · 4013240-871
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Stack plies of prepreg per par. 4.4.1.1 on a teflon released pressure plate. Place one (1) ply of one (1) mil thick porous Release Ease (or equivalent) and five (5) plies of 7781 glass bleeder on the stack. Bag with Kapton and high temperature bag sealant. Apply 3-5 inches Hg vacuum. Raise temperature at 3-5°F per minute to 180 ± 5°F and hold 55-65 minutes. Raise temperature at 3-5°F per minute to 400± 5°F and hold for 40-50 minutes. After hold period, apply full vacuum pressure and heat to 570-580°F at 3-5°F per minute. At 445-455°F add 145-155 psi autoclave pressure. Hold 575°F, 150 psi autoclave and full vacuum for 180-190 minutes. Cool slowly under pressure. Post cure per manufacturers recommendation. (Normally 10 to 24 hours at 600°F)

4.4.2 Physical Properties

4.4.2.1 Resin Content. Samples, weighing from one to two grams, taken from the cured laminate, which are representative of each lot shall be tested as follows:

(a) Dry the sample for a minimum of one hour at 300°F ±10 (149°C±6).
(b) Cool in a desiccator to room temperature and weigh sample to the nearest 0.001 gram (W_1).
(c) Place sample in a 250 cm^3 Eilenmeyer flask equipped with ground glass joints and add 20 cm^3 of sulfuric acid, 1.84 specific gravity, and heat under condensers until fuming.
(d) Digest until the composite is visibly disintegrated and resin and fiber particles are dispersed throughout the solution.
(e) Transfer to a convenient size beaker and add 30 percent hydrogen peroxide drop wise until the solution is water white.
(f) At this point add two more cm^3 of 30 percent hydrogen peroxide to the solution and fume the acid solution for an additional ten minutes to ensure complete decomposition of the polymer.
(g) Cool the mixture to 75°F ± 5 (24°C ± 3).
(h) Collect the fibers by vacuum filtration through a medium porosity-sintered glass crucible that has been weighed to the nearest 0.001 gram (W_2).
(i) After the sulfuric acid has been filtered off, wash the fibers in the crucible thoroughly with 600 cm^3 of distilled water, added a few cm^3 at a time. Rinse with acetone to remove all moisture.
(j) Remove the crucible from the filtering system and place in an open beaker.
(k) Dry fibers for a minimum of 45 minutes at 325°F ± 10 (163°C ± 6), cool in a desiccator, and weigh to the nearest 0.001 gram (W_3).
(l) Resin content, measured to the nearest 0.1 percent, shall be calculated as follows:

$$\text{Percent Resin Content} = \frac{W_1 - (W_2 - W_3)}{W_1} \times 100$$

LTR	DESCRIPTION	DATE	APPROVED
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4.4.2.2 Fiber Content. Fiber content of the cured laminate shall be calculated as follows:

$$\frac{\text{Percent Resin content (Weight fraction of resin)}}{\text{Specific gravity of resin}}+$$

$$\frac{\text{Percent Fiber Content (Weight fraction of fiber)}}{\text{Specific gravity of fiber}}=$$

Total volume of cured laminate sample

$$\text{Percent volume of fiber} = \frac{\text{Volume of fiber}}{\text{Total volume}} \times 100$$

EXAMPLE: Resin Content of cured laminate sample = 30%
Therefore: Fiber content = 70%

$$\frac{30}{1.308} + \frac{70}{1.76} = 22.94 + 39.77 = 62.71 \text{ Total Volume}$$

$$\text{Percent Fiber Volume} = \frac{39.77}{62.71} \times 100 = 63.4$$

NOTE: The density of the appropriate lots of fiber and resin utilized in the laminate shall be determined from certifications and test results received.

4.4.2.3 **Void Content. Void content of the cured laminate shall be calculated as follows:**

$$\text{Void Content, Volume Percent} = 100 - pL\left(\frac{R}{pr} + \frac{F}{pf}\right)$$

Where: p_L = density of the laminate determined using, FED-STD-406, Method 4011, g/cm^3
R = resin content from 3.4.1.1, weight percent
F = fiber content (100-R), weight percent
pr = density of the resin used in the laminate, from the appropriate certifications and test results
pf = density of the fiber used in the laminate, from the appropriate certifications and test results.

4.4.2.4 Specific Gravity. Specific gravity shall be determined per FED-STD-406, Method 5011.

4.4.2.5 Thickness. Thickness of cured laminate per ply shall be determined by measuring the thickness of the laminate at five random locations to the nearest .0001 inch

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON: FRACTIONS ± DECIMALS ± ANGLES ±	SIGNATURES	DAY	MO	YR	GENERAL ELECTRIC DEPT LCC
	DRAWN L. J. Angel	10	12	80	
	CHECKED C. Laurie	12	13	80	SPECIFICATION FOR PMR-15 PRE-IMPREGNATED WOVEN FIBERGLASS FABRIC
	ISSUED H. Meyer	12	12	80	
ALL SURFACES ✓	ENGRG				
MATL	MFG				
	MATL Wallace	12	13	80	
					SIZE A · CODE IDENT NO. 07482 · 4013240-871
					SCALE · SHEET 9 of 13

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(0.0025 mm). The readings are averaged and divided by the number of plies; this value is the cured laminate thickness per ply.

4.4.3 Mechanical Properties

4.4.3.1 Tensile Strength and Modulus. Tensile strength and modulus shall be determined per FTMS 406 Method 1011 Type 1.

4.4.3.2 Flexural Strength and Modulus. Flexural strength and modulus shall be determined per ASTM D790 Method I.

4.4.3.2.1 Test conditions. Unless otherwise specified by the Purchaser, the specimen shall be tested to failure under three point flexure over a 32:1 ± 15 percent span-to-depth ratio using nominal .125 inch (3.18 mm) radius steel rods for load and reaction supports. Specimen shall be loaded to failure in a universal testing machine capable of recording specimen deflection at a load rate of .05 inches (1.27 mm) per minute.

4.4.3.2.2 Calculations. The flexural strength and modulus shall be calculated from the following formulae:

Flexural Strength (S)

U.S. Units $\quad lbs/in^2 \quad = \quad \frac{3PL}{2\,bd^2}$

SI Units $\quad (MPa) \quad = \quad \frac{3PL}{2\,bd^2} \times 10^6$

WHERE: P = ultimate failure load in pounds (MN) to the nearest pound (MN)
L = span length in inches (mm) to the nearest .005 inch (0.13 mm)
b = specimen width in inches (mm) to the nearest .001 inch (0.025 mm)
d = specimen thickness in inches (mm) to the nearest .0005 inch (0.013 mm)

Flexural Modulus (E_B)

U.S. Units $\quad lbs/in^2 \quad = \quad \frac{L^3M}{4\,bd^3}$

SI Units $\quad MPa \quad = \quad \frac{L^3M^{\prime\prime}}{4\,bd^3}$

Where: L = span length in inches (mm) to the nearest .005 inch (0.13 mm)
M = initial slope of the load-deflection curve in inches (m) as measured by deflectometer to the nearest .0001 inch (0.0025 mm)
b = specimen width in inches (mm) to the nearest .001 inch (0.025mm)
d = specimen thickness in inches (mm) to the nearest .0005 inch (0.013 mm)

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON: FRACTIONS DECIMALS ANGLES ± ± ±
ALL SURFACES ✓
MAT'L

SIGNATURES	DAY	MO	YR
DRAWN [illegible]	16	12	80
CHECKED [illegible]	12	12	80
ISSUED [illegible]	18	12	80
ENGRG			
MFG			
MATL [illegible]	12	13	80

GENERAL ELECTRIC DEPT LOC

SPECIFICATION FOR PMR-15 PRE-IMPREGNATED WOVEN FIBERGLASS FABRIC

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NOTE: In calculating the flexural modulus in Standard International (SI) units, all millimeter values should be converted to the appropriate value in meters in order to make the expression dimensionally correct.

4.4.3.3 Short Beam Shear Strength. Short beam shear strength shall be determined per ASTM D2344 with the following exceptions and additions.

4.4.3.3.1 Specimen Description. Unless otherwise specified by the Purchaser, the test specimen shall be fabricated to the following dimensions:

Length (L) = $2.00 \pm .015$
Width (W) = $0.50 \pm .01$
Thickness (T) = .100 to .124
Load Rate .05 in/min.

NOTE: Width and thickness of specimen shall be measure using a .157 inch (4.00 mm) radius dual face ball anvil micrometer.

4.4.3.3.2 Test Conditions. Unless otherwise specified by the Purchaser, the specimen shall be loaded to failure using a .125 inch (3.18 mm) radius steel rod as the loading nose. When testing at temperatures other than ambient, specimens shall be held for 10+1,-0 minutes at the test temperature prior to testing.

4.4.3.3.3 Calculations. The short beam shear strength shall be calculated from the following formula:

Short Beam Shear Strength(S)

U.S. Units $\quad \text{lbs/in}^2 = \dfrac{3P}{4Wt}$

SI Units $\quad \text{(MPa)} = \dfrac{3P}{(4Wt) \times 10^3}$

Where: P = ultimate failure load in pounds (MN) to the nearest pound (MN)
W = specimens width in inches (mm) to the nearest .001 inch (0.025 mm)
t = specimen thickness in inches (mm) to the neares .0005 inche (0.013 mm)

5. PREPARATION FOR DELIVERY

5.1 Packing

5.1.1 Unless otherwise specified, fabric shall be wound on spools of not less than three inches (76 mm) diameter and interleaved with a contrasting color separator film. Tape

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON:	SIGNATURES	DAY	MO	YR	GENERAL ELECTRIC DEPT LOC
FRACTIONS ± DECIMALS ± ANGLES ±	DRAWN				SPECIFICATION FOR PMR-15 PRE-IMPREGNATED WOVEN FIBERGLASS FABRIC
ALL SURFACES ✓	CHECKED	12	13	80	
MATL	ISSUED	18	12	80	
	ENGRG				SIZE A · CODE IDENT NO. 07482 · 4013240-871
	MFG				SCALE · SHEET 11 of 13
	MATL	12	13	80	DIST TO NP

LTR	DESCRIPTION	DATE	APPROVED

ends shall be secured. Each spool of pre-impregnated material shall be wrapped individually in a material which will ensure protection from damage that may result from handling, shipping and storage.

5.2 Marking

5.2.1 The following information shall be included on the exterior of each shipping container and on a label located on each spool of material.

(a) Purchase order number
(b) Manufacturer's name
(c) Date of manufacture
(d) Lot number
(e) Spool number and length
(f) Specification number, CLASS, and revision number

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON:
FRACTIONS DECIMALS ANGLES
ALL SURFACES ✓
MATL

SIGNATURES	DAY	MO	YR
DRAWN			
CHECKED	12	13	80
ISSUED	18	12	80
ENGRG			
MFG			
MATL	12	13	80

GENERAL ELECTRIC

SPECIFICATION FOR PMR-15 PRE-IMPREGNATED WOVEN FIBERGLASS FABRIC

SIZE A CODE IDENT NO. 07482 4013240-871

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A	4013240-871	13	

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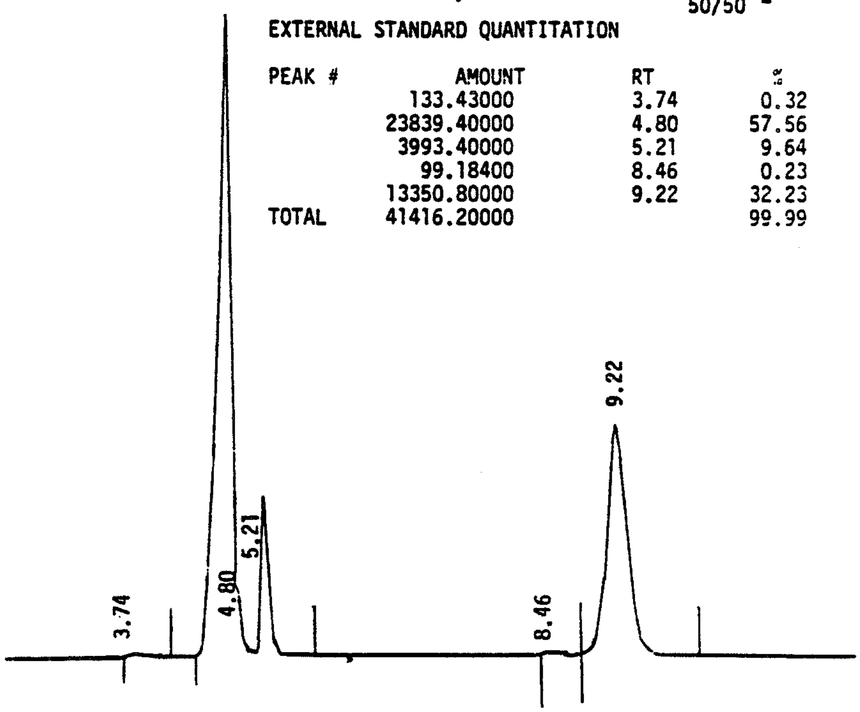
Aug. 12, 1980 15:21:30 Chart 2.00 CM/MIN Flow 1.00 ML/MIN
PRESSURE 4100.0 DETECTOR 254/050
SAMPLE #9 RUN #11 CALC =0
COLUMN 3 X 60A° μ PORASIL SOLVENT MeOH/H_2O 50/50 OPR ID: 10

EXTERNAL STANDARD QUANTITATION

PEAK #	AMOUNT	RT	%
	133.43000	3.74	0.32
	23839.40000	4.80	57.56
	3993.40000	5.21	9.64
	99.18400	8.46	0.23
	13350.80000	9.22	32.23
TOTAL	41416.20000		99.99



5.3 STANDARD
HPLC SIGNATURE - PMR15

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON:	SIGNATURES	DAY	MO	YR	GENERAL ELECTRIC
FRACTIONS ± DECIMALS ± ANGLES ±	DRAWN				DEPT LOC
	CHECKED C. Lionetti	12	13	80	SPECIFICATION FOR PMR-15 PRE-IMPREGNATED WOVEN FIBERGLASS FABRIC
	ISSUED	18	12	80	
	ENGRG				
ALL SURFACES ✓	MFG				
MATL	MATL	12	13	80	SIZE A · CODE IDENT NO. 07482 · 4013240-871
					SCALE · SHEET 13 of 13

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APPENDIX B

MATERIAL	FOR
PMR 15/GRAPHITE*	COMPOSITE LAMINATE

SPECIFICATION
A50TF223 CL-B

APPLICABLE TO	PROPERTY
0 DEGREE, +- 45 DEGREES, 0 DEGREE 4 PLY SPECIMEN: RECTANGULAR GAGE 1" X .052" (YOKEL) TESTED: 0 DEGREE DIRECTION * MATERIAL SUPPLIED BY FERRO CORP.	ULTIMATE TENSILE STRENGTH

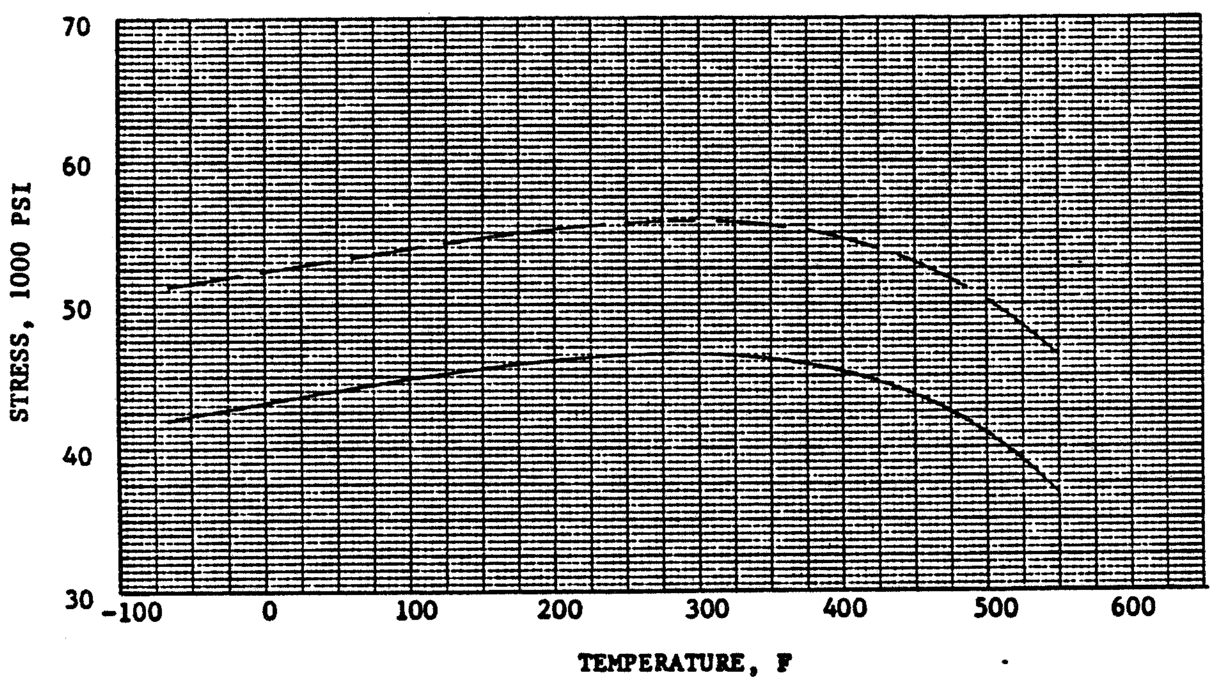
TEMPERATURE	TIME AT TEST TEMP	R_T

ORIENTATION

LIMITING TEMP

——— : MINIMUM (≥ 95% CONFIDENCE OF 99% EXCEEDENCE)

— — — : $\overline{X}$ (AVERAGE)



PMR 15/GRAPHITE* COMPOSITE LAMINATE

SPECIFICATION

A50TF223 CL-B

PROPERTY

ULTIMATE COMPRESSIVE STRENGTH

TEMPERATURE	TIME AT TEST TEMP	θ_T

ORIENTATION

LIMITING TEMP.

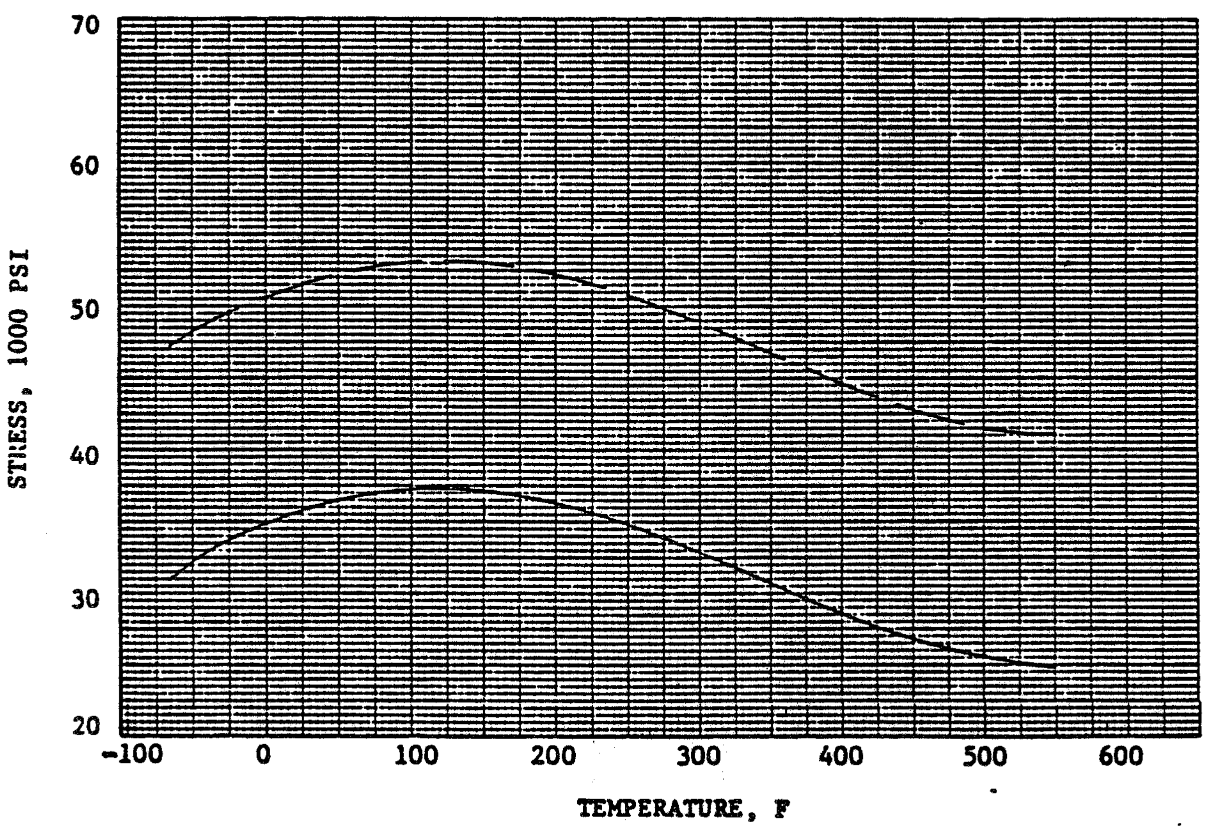
APPLICABLE TO

0 DEGREE, +- 45 DEGREES, 0 DEGREE 8 PLY
SPECIMEN: DOGBONE
TESTED: 0 DEGREE DIRECTION

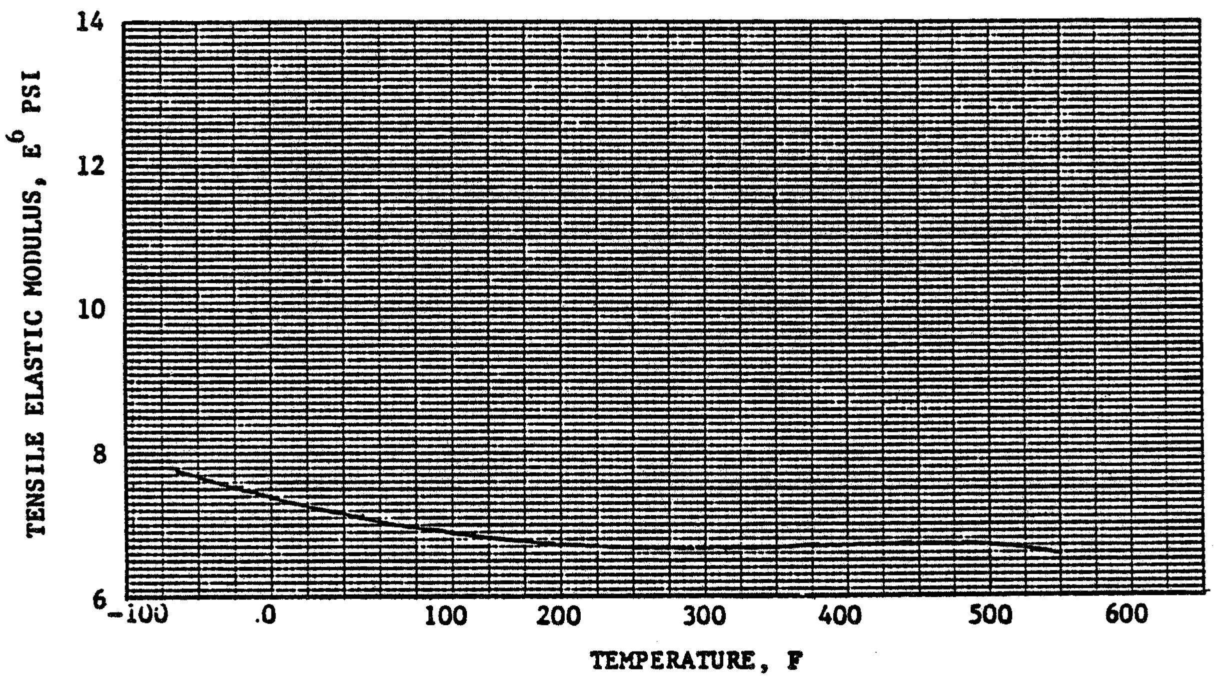
* MATERIAL SUPPLIED BY FERRO CORP.

———— : MINIMUM (≥ 95% CONFIDENCE OF 99% EXCEEDENCE)

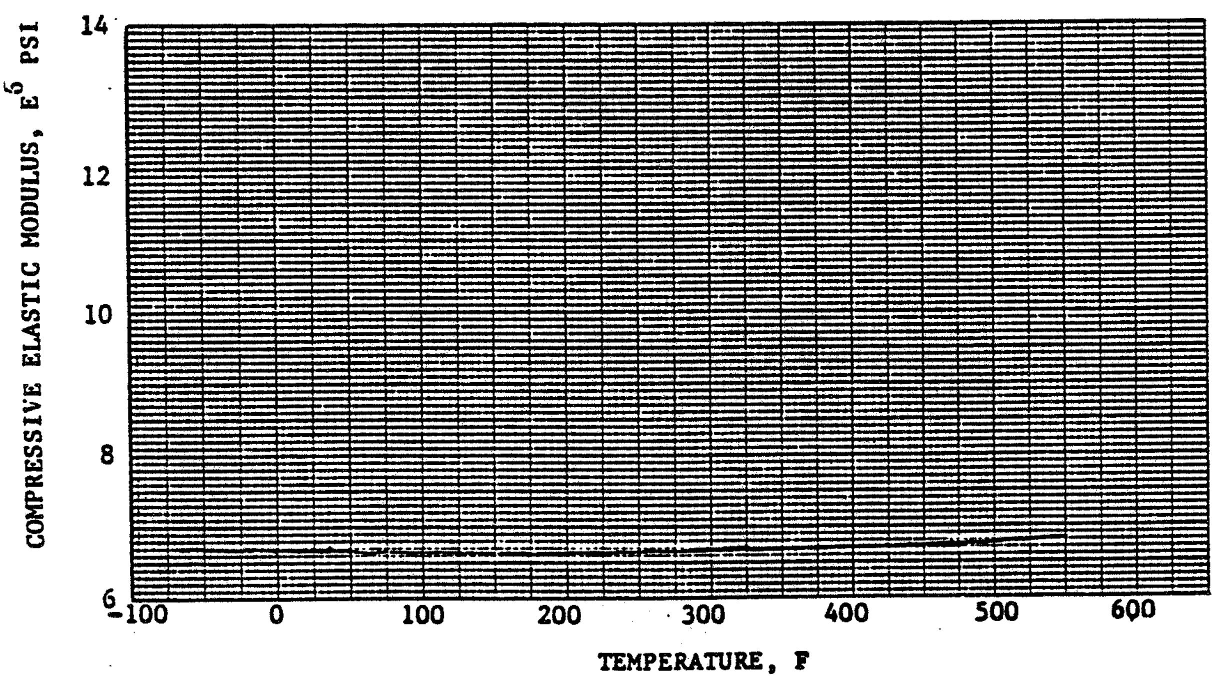
— — — : $\bar{X}$ (AVERAGE)



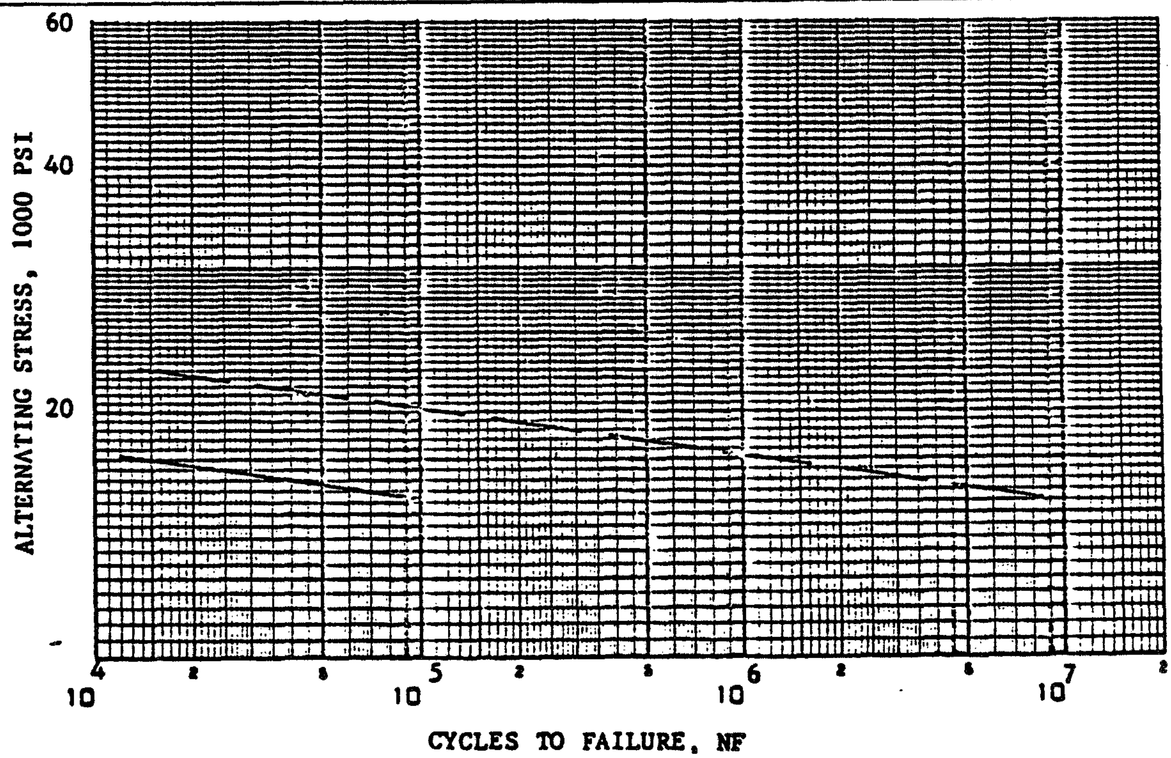
	MATERIAL: PMR 15/GRAPHITE* — FORM: COMPOSITE LAMINATE
	SPECIFICATION: A50TF223 CL-B
APPLICABLE TO: 0 DEGREE, +- 45 DEGREES, 0 DEGREE 4 PLY SPECIMEN: RECTANGULAR GAGE 1" X .052" (YOKEL) TESTED: 0 DEGREE DIRECTION * MATERIAL SUPPLIED BY FERRO CORP.	PROPERTY: STATIC TENSILE MODULUS OF ELASTICITY
	EQUATION: STATIC MODULUS = 7.346051 - 5.17315E-3T + 96.74985E - 7T↑2 - 3.09186E - 17T↑6
	REFERENCE TEMP.
AVERAGE PROPERTIES. ———— : $\bar{X}$	STD. DEV. = .319



	MATERIAL: PMR 15/GRAPHITE* — FORM: COMPOSITE LAMINATE
	SPECIFICATION: A50TF223 CL-B
0 DEGREE, +- 45 DEGREES, 0 DEGREE 8 PLY SPECIMEN: DOGBONE TESTED: 0 DEGREE DIRECTION * MATERIAL SUPPLIED BY FERRO CORP.	PROPERTY: STATIC COMPRESSIVE MODULUS OF ELASTICITY
	EQUATION: MOD = 6.642293 - 3.3949E - 4T + 12.02338E - 7T↑2
	REFERENCE TEMP.
AVERAGE PROPERTIES. ——— : $\bar{X}$	STD. DEV. = .229



MATERIAL: PMR 15/GRAPHITE*	CODE: COMPOSITE LAMINATE
	SPECIFICATION: A50TF223 CL-B
APPLICABLE TO: 0 DEGREES +- 45 DEGREES 4 PLY SPECIMEN: RECTANGULAR GAGE 1.2" X .052" (YOKEL) TESTED: 0 DEGREE DIRECTION * MATERIAL SUPPLIED BY FERRO CORP.	PROPERTY: TENSILE FATIGUE(HCF): LOAD, NF TEMPERATURE: 75 — A-RATIO: 0.818 — K_T: TEST TYPE: FREQUENCY: 1800 CPM (30 HZ) — HOLD TIME: — RAMP TIME: TEST MODULUS, E (10^6 PSI): — ANNULAR GAGE SECT., R': ORIENTATION:
——— : MINIMUM (≥ 95% CONFIDENCE OF 99% EXCEEDENCE)	— — — : $\bar{X}$ (AVERAGE)



MATERIAL: PMR 15/GRAPHITE* | FORM: COMPOSITE LAMINATE

SPECIFICATION: A50TF223 CL-B

PROPERTY: TENSILE FATIGUE(HCF): LOAD, NF

APPLICABLE TO:
0 DEGREES +- 45 DEGREES 4 PLY
SPECIMEN: RECTANGULAR GAGE 1.2" X .052"
(YOKEL)
TESTED: 0 DEGREE DIRECTION

* MATERIAL SUPPLIED BY FERRO CORP.

TEMPERATURE	A-RATIO	K_T
350	0.818	

TEST TYPE

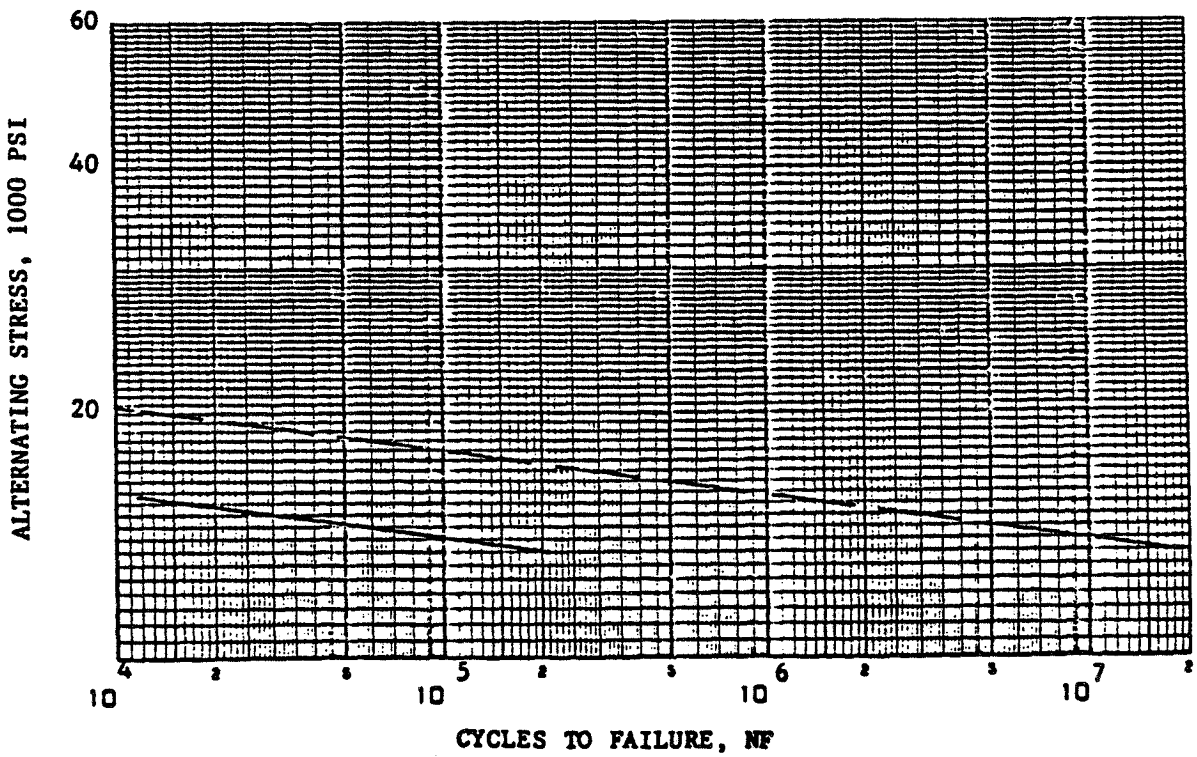
FREQUENCY	HOLD TIME	RAMP TIME
1800 CPM (30 HZ)		

TEST MODULUS, E (10^6 PSI) | ANNULAR GAGE SECT., R'

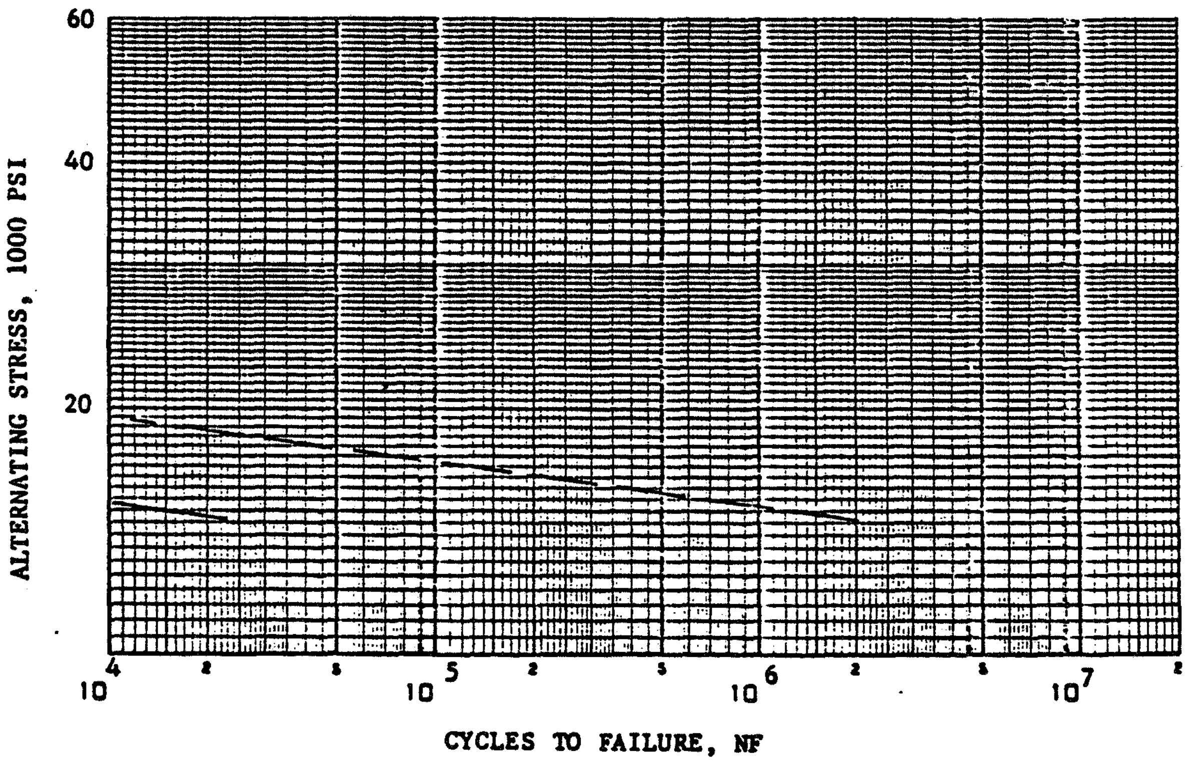
ORIENTATION

———— : MINIMUM (≥ 95% CONFIDENCE OF 99% EXCEEDENCE)

— — — : $\bar{X}$ (AVERAGE)



	MATERIAL: PMR 15/GRAPHITE* COMPOSITE LAMINATE
	SPECIFICATION: A50TF223 CL-B
APPLICABLE TO: 0 DEGREES +- 45 DEGREES 4 PLY SPECIMEN: RECTANGULAR GAGE 1.2" X .052" (YOKEL) TESTED: 0 DEGREE DIRECTION * MATERIAL SUPPLIED BY FERRO CORP.	PROPERTY: TENSILE FATIGUE(HCF): LOAD, NF
	TEMPERATURE: 450 | A-RATIO: 0.818 | K_T:
	TEST TYPE:
	FREQUENCY: 1800 CPM (30 HZ) | HOLD TIME: | RAMP TIME:
	TEST MODULUS, E (10^6 PSI): | ANNULAR GAGE SECT., R':
	ORIENTATION:
——— : MINIMUM (≥ 95% CONFIDENCE OF 99% EXCEEDENCE)	— — — : $\overline{X}$ (AVERAGE)



MATERIAL		FORM
PMR 15/GRAPHITE*		COMPOSITE LAMINATE

SPECIFICATION
A50TF223 CL-B

APPLICABLE TO	PROPERTY
0 DEGREES +- 45 DEGREES 4 PLY SPECIMEN: RECTANGULAR GAGE 1.2" X .052" (YOKEL) TESTED: 0 DEGREE DIRECTION * MATERIAL SUPPLIED BY FERRO CORP.	TENSILE FATIGUE(HCF): LOAD, NF

TEMPERATURE	A-RATIO	K_T
500	0.818	

TEST TYPE		

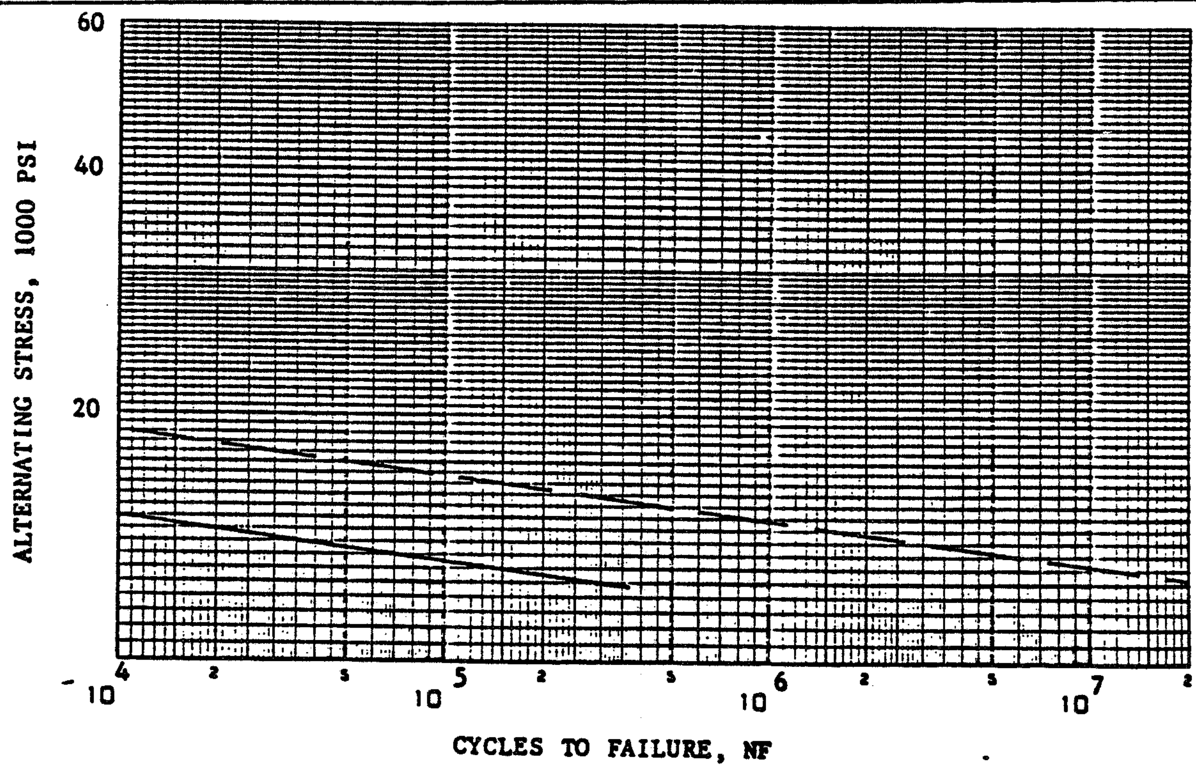
FREQUENCY	HOLD TIME	RAMP TIME
1800 CPM (30 HZ)		

TEST MODULUS, E (10^6 PSI)	ANNULAR GAGE SECT., R'

ORIENTATION

———— : MINIMUM (≥ 95% CONFIDENCE OF 99% EXCEEDENCE)

— — — : $\bar{X}$ (AVERAGE)



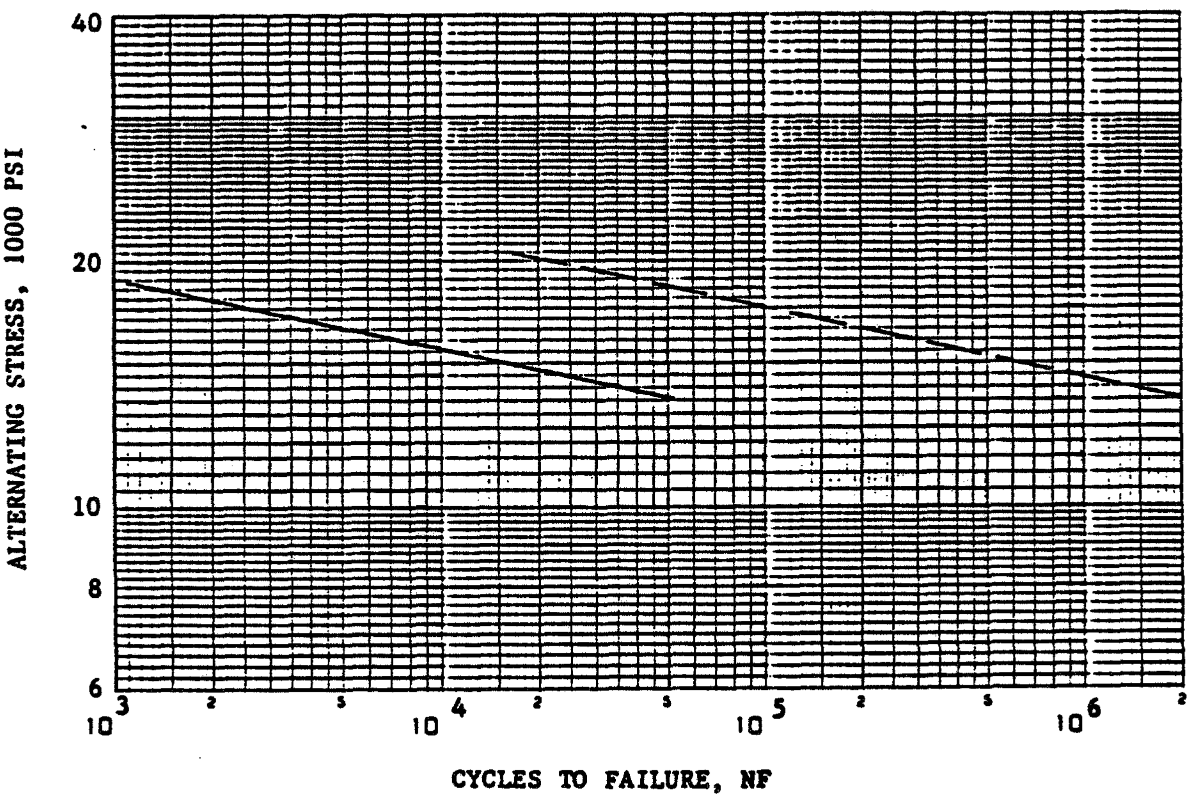
MATERIAL	PMR 15/GRAPHITE* COMPOSITE LAMINATE
SPECIFICATION	A50TF223 CL-B
PROPERTY	COMPRESSIVE FATIGUE(HCF): LOAD,NF
TEMPERATURE	75
A-RATIO	-0.818
TEST TYPE	
FREQUENCY	1800 CPM (30 HZ)
HOLD TIME	
RAMP TIME	
TEST MODULUS, E (10^6 PSI)	
ANNULAR GAGE SECT., R"	
ORIENTATION	

APPLICABLE TO
0 DEGREES +- 45 DEGREES 4 PLY
SPECIMEN: DOGBONE
TESTED: 0 DEGREE DIRECTION

* MATERIAL SUPPLIED BY FERRO CORP.

——— : MINIMUM ($\geq$ 95% CONFIDENCE OF 99% EXCEEDENCE)

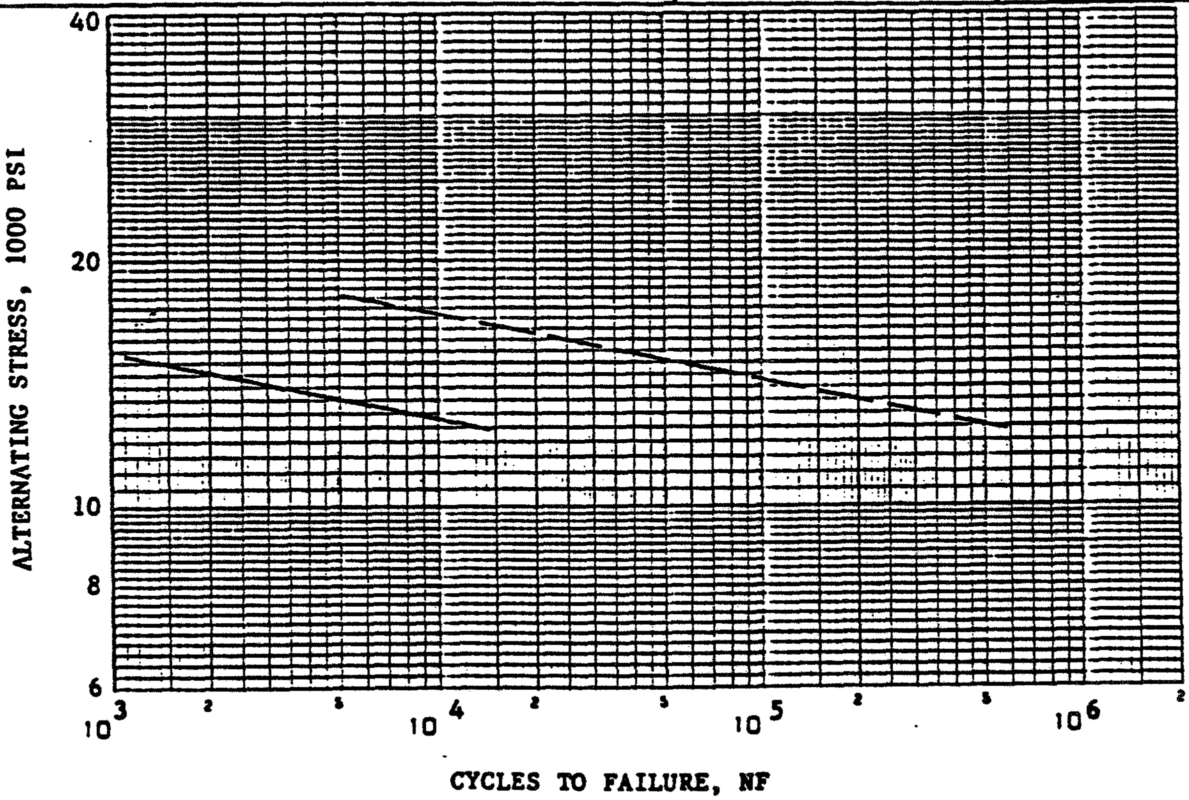
— — — : $\overline{X}$ (AVERAGE)



	MATERIAL: PMR 15/GRAPHITE* COMPOSITE LAMINATE
	SPECIFICATION: A50TF223 CL-B
APPLICABLE TO: 0 DEGREES +- 45 DEGREES 4 PLY SPECIMEN: DOGBONE TESTED: 0 DEGREE DIRECTION * MATERIAL SUPPLIED BY FERRO CORP.	PROPERTY: COMPRESSIVE FATIGUE(HCF): LOAD,NF
	TEMPERATURE: 350 | A-RATIO: -0.818 | R:
	TEST TYPE:
	FREQUENCY: 1800 CPM (30 HZ) | HOLD TIME: | RAMP TIME:
	TEST MODULUS, E (10^6 PSI): | ANNULAR GAGE SECT., R:
	ORIENTATION:

——— : MINIMUM (≥ 95% CONFIDENCE OF 99% EXCEEDENCE)

— — — : $\overline{X}$ (AVERAGE)



MATERIAL

PMR 15/GRAPHITE* COMPOSITE LAMINATE

SPECIFICATION

A50TF223 CL-B

APPLICABLE TO

0 DEGREES +- 45 DEGREES 4 PLY
SPECIMEN: DOGBONE
TESTED: 0 DEGREE DIRECTION

* MATERIAL SUPPLIED BY FERRO CORP.

PROPERTY

COMPRESSIVE FATIGUE(HCF): LOAD,NF

TEMPERATURE	A-RATIO	K_T
450	-0.818	

TEST TYPE

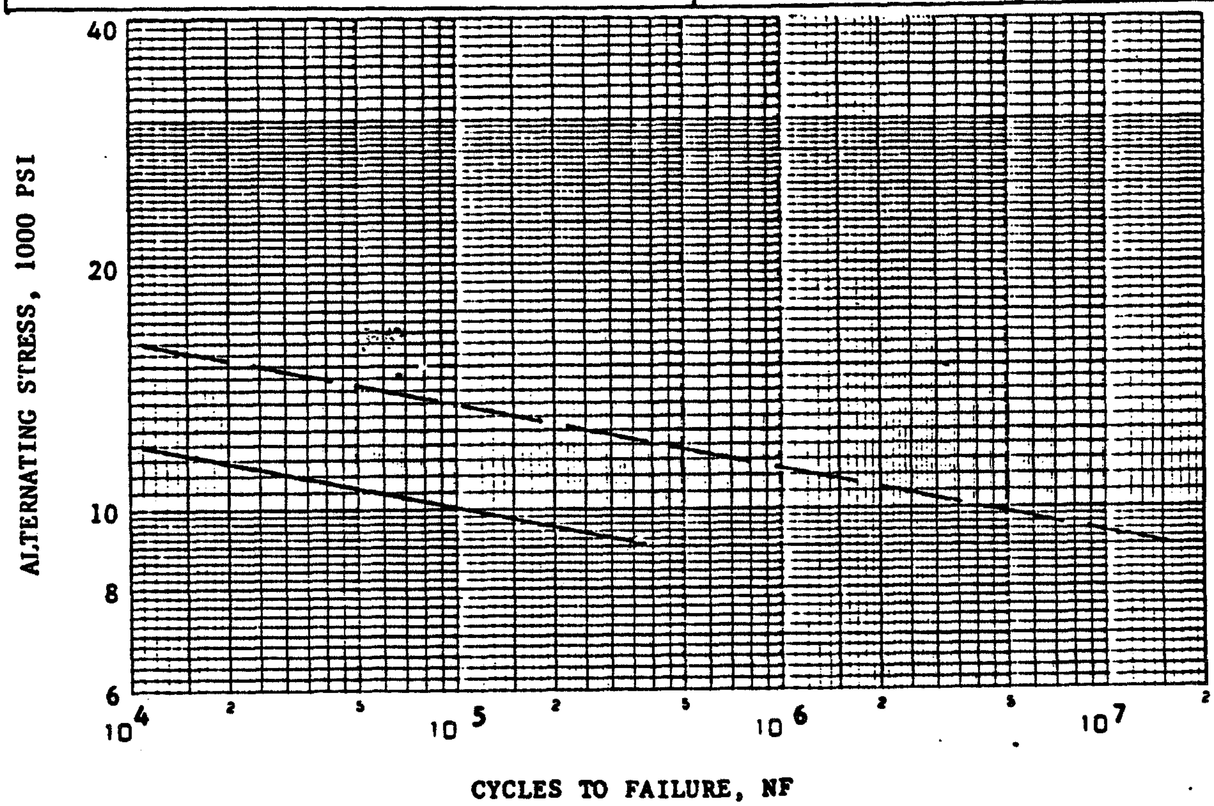
FREQUENCY	HOLD TIME	RAMP TIME
1800 CPM (30 HZ)		

TEST MODULUS, E (10^6 PSI)	ANNULAR GAGE SECTION

ORIENTATION

———— : MINIMUM (≥ 95% CONFIDENCE OF 99% EXCEEDENCE)

— — — : $\overline{X}$ (AVERAGE)



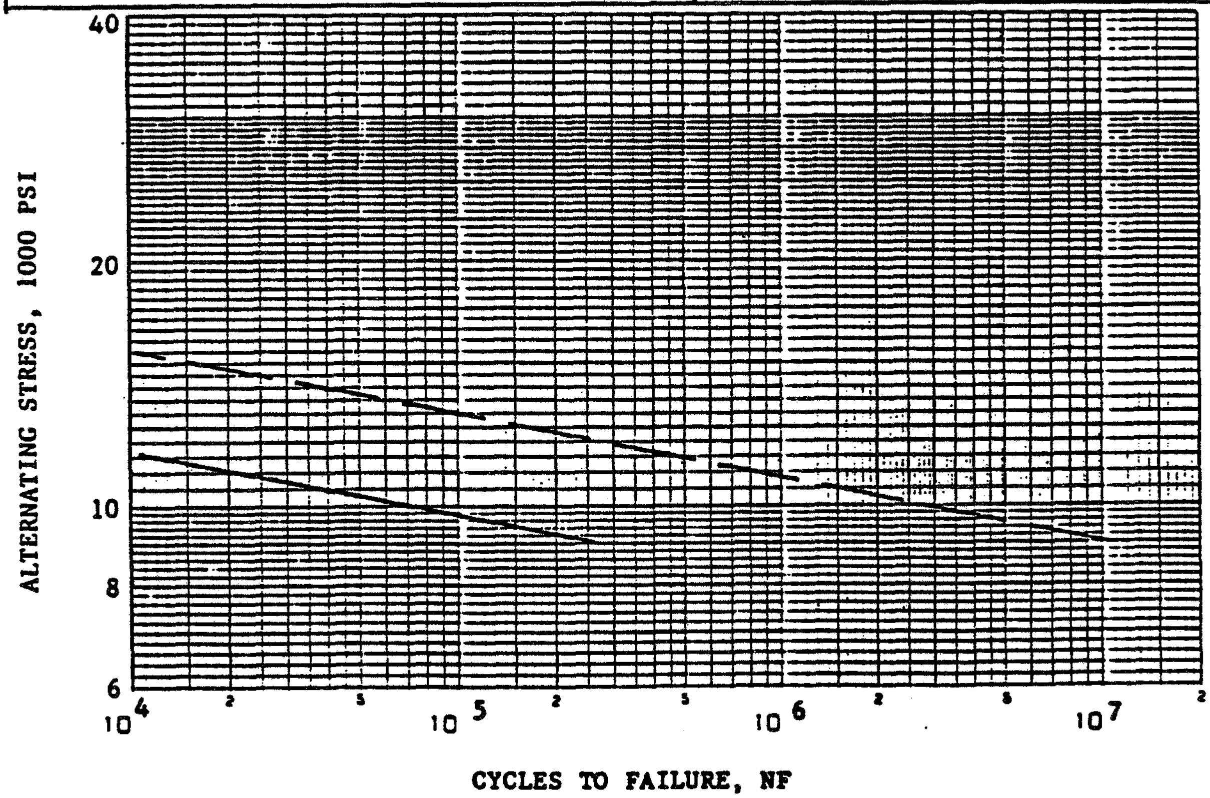
MATERIAL	PMR 15/GRAPHITE* COMPOSITE LAMINATE
SPECIFICATION	A50TF223 CL-B
PROPERTY	COMPRESSIVE FATIGUE(HCF): LOAD,NF
TEMPERATURE	500
A-RATIO	-0.818
K_T	
TEST TYPE	
FREQUENCY	1800 CPM (30 HZ)
HOLD TIME	
RAMP TIME	
TEST MODULUS, E (10^6 PSI)	
ANNULAR GAGE SECT., R	
ORIENTATION	

APPLICABLE TO:
0 DEGREES +- 45 DEGREES 4 PLY
SPECIMEN: DOGBONE
TESTED: 0 DEGREE DIRECTION

* MATERIAL SUPPLIED BY FERRO CORP.

——— : MINIMUM ($\geq$ 95% CONFIDENCE OF 99% EXCEEDENCE)

— — — : $\overline{X}$ (AVERAGE)



RAIL SHEAR STRENGTH

4 PLY (0, ±45, 0)$_T$ T-300-3K-BHS/PMR15 LAMINATE

TEST TEMPERATURE	LOT NO.	PANEL NO.	PANEL RESIN CONTENT % WT.	PANEL VOID %	PANEL DENSITY GM/CC	SPECIMEN NO.	RAIL SHEAR STRENGTH PSI
-65 F	USP G9515 (B)	G15-2/4	27.6	2.75	1.56	BS1	26,770
		DO				BS2	25,700
	FERRO 12072 (C)	F72-1A/4	30.4	1.40	1.57	CS1	24,710
	FERRO 12073 (D)	F73-1A/4	31.3	0.77	1.58	DS1	26,710
						AVG.	25,970
73°F	USP G9456 (A)	28	26.0	2.63	1.57	1	33,180
		DO				2	30,020
		DO				3	32,680
		DO	26.6	2.14	1.58	4	30,620
	USP G9515 (B)	G15-3/4	28.3	2.03	1.57	BS3	26,300
	FERRO 12072 (C)	F72-1A/4	30.4	1.40	1.57	CS2	23,990
	FERRO 12073 (D)	F73-1A/4	31.3	0.77	1.58	DS2	23,410
						AVG.	28,600
350°F	USP G9515 (B)	G15-2/4	27.6	2.75	1.56	BS7 ∡(1)	24,170
		DO				BS8 ∡(1)	23,140
						AVG.	23,655
350°F	USP G9456 (A)	20	26.6	2.14	1.58	1	18,670
	USP G9456 (A)	21	26.5	2.68	1.57	2	23,340
		DO				3	21,090
		DO				4	19,650
	USP G9515 (B)	G15-3/4	28.3	2.03	1.57	BS4	21,560
	FERRO 12072 (C)	F72-1A/4	30.4	1.40	1.57	CS3	24,480
	FERRO 12073 (D)	F73-1A/4	31.3	0.77	1.58	DS3	18,180
						AVG.	20,996
450°F	USP G9515 (B)	G15-3/4	28.3	2.03	1.57	BS5	21,840
	FERRO 12072 (C)	F72-1B/4	29.8	1.68	1.57	CS4	17,970
	FERRO 12073 (D)	F73-1A/4	31.3	0.77	1.58	DS3	18,180
	USP G9515 (B)(2)	G15-4/4	29.2	1.80	1.57	BS1	20,510
						AVG.	21,015
550°F	USP 9456 (A)	27	27.7	2.92	1.56	1	21,150
		DO				2	23,950
	USP G9456 (A)	17	26.7	2.26	1.58	3	18,160
		DO				4	21,420
	USP 9515	G15-3/4	28.3	2.03	1.57	BS6	19,970
	FERRO 12072 (C)	F72-1B/4	29.8	1.68	1.57	CS6	21,900
	FERRO 12073 (D)	F73-1B/4	30.6	0.86	1.58	DS5	26,260
		DO				DS6	22,120
						AVG.	21,866

SPECIMEN CONFIGURATION AND TEST METHOD PER GE 4013179-360

(1) SPECIMENS PREPARED AT 22 1/2° ∡ TO WARP DIRECTION

(2) ADDED DATA POINT

LAMINATE FLEXURAL STRENGTH & MODULUS of T300-3K-8HS/PMR15 Before & After Exposure to Moisture

PANEL #	EXPOSURE	CONDITION OF SPECIMEN	TEST TEMPERATURE ^{o}F (^{o}C)	SPECIMEN NUMBER	FLEXURAL PROPERTIES STRENGTH Psi	MODULUS E X 10^{6} Psi
19	None	Dry	$73^{o}F$ ($23^{o}C$)	1	129,890	10.5
				2	117,140	10.7
				3	115,290	10.4
				4	122,590	10.4
				5	136,320	10.2
				Avg.	124,246	10.4
19	$180^{o}F$ & 98% RH for 30 days	Fully Saturated 1.3% Moisture		1	132,580	9.2
				2	133,570	9.4
				3	124,860	9.0
				4	134,790	9.4
				5	134,630	9.4
				Avg.	132,086	9.28
19	None	Dry	$350^{o}F$ (176^{o})	1	129,630	9.4
				2	122,930	9.7
				3	116,920	9.6
				4	134,000	9.5
				5	118,750	9.2
				Avg.	124,446	9.48
19	$180^{o}F$ & 98% RH for 30 days	Fully Saturated (1.3% Moisture 3 days @ $250^{o}F$ to 0% moisture level		1	106,160	8.4
				2	109,280	8.6
				3	105,190	8.3
				4	103,980	8.0
				5	88,300	8.1
				Avg.	102,582	8.28

1000 HOUR CREEP RUPTURE

LOT NO	PANEL NO.	PANEL RESIN % WT.	PANEL VOID %	PANEL DENSITY GM/CC	SPECIMEN NUMBER (1)	TEMP °F	STRESS KSI	TIME FOR % CREEP HRS. .1%	.2%	.5%	1.0%	TIME TO RUPTURE HRS	TEST DISCONTINUED HRS.	TEST DISCONTINUED %CREEP
FERRO 12073 (D)	F73-2/y	30.2	1.4	1.57	DT24	RT	42	---	---	---	---	FAILED ON LOADING	---	---
FERRO 12072 (C)	F72-2/y	31.6	1.5	1.56	CT24	RT	45	---	---	---	---	---	1030	.075
USPG 9516 (E)	G16-3/y	28.6	0.1	1.58	ET24	RT	50	---	---	---	---	---	1127	.078
USPG 9515 (B)	G15-6/y	27.6	2.3	1.55	BT35	RT	52.5	---	---	---	---	---	1170	.090
FERRO 12072 (C)	F72-2/y	31.6	1.5	1.56	CT25	350	40.	725	865	---	---	---	1007	.310
FERRO 12073 (D)	F73-2/y	30.2	1.4	1.57	DT25	350	40	---	---	---	---	273	---	.060
USPG 9516 (E)	G16-3/y	28.6	0.1	1.58	ET25	350	45	---	---	---	---	---	1147	.088
USPG 9515 (B)	G15-6/y	27.6	2.3	1.55	BT36	350	45	11	33	325	---	---	1025	.730
FERRO 12072 (C)	F72-2/y	31.6	1.5	1.56	CT26	450	40	250	625	---	---	---	1027	.290
USPG 9515 (B)	G15-6/y	27.6	2.3	1.55	BT37	450	40	20	70	410	---	---	1190	.93
FERRO 12073 (D)	F73-2/y	30.2	1.4	1.57	DT26	450	45	---	---	---	---	104	---	.081
USPG 9516 (E)	G15-3/y	28.6	o.1	1.58	ET26	450	45	10	120	---	---	524	---	.285

(1) Specimen Type - See Yokel Specimen (0±45,0)$_T$ Figure 3

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15. Supplementary Notes

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16. Abstract

The objective of this program was to demonstrate the cost and weight advantages that could be obtained by utilizing the graphite/PMR15 material system to replace titanium in selected turbofan engine applications.

The first component to be selected as a basis for evaluation was the outer bypass duct of the General Electric F404 engine. The operating environment of this duct was defined and then an extensive mechanical and physical property test program was conducted using material made by processing techniques which were also established by this program. Based on these properties, design concepts to fabricate a composite version of the duct were established and two complete ducts fabricated. One of these ducts was proof pressure tested and then run successfully on a factory test engine for over 1900 hours. The second duct was static tested to 210% design limit load without failure.

An improved design was then developed which utilized integral composite end flanges. A complete duct was fabricated and successfully proof pressure tested. The net results of this effort showed that a composite version of the outer duct would be 14% lighter and 30% less expensive that the titanium duct.

The other type of structure choosen for investigation was the F404 fan stator assembly, including the fan stator vanes. It was concluded that it was feasible to utilize composite materials for this type structure but that the requirements imposed by replacing an existing metal design resulted in an inefficient composite design. It was concluded that if composites were to be effectively used in this type structure, the design must be tailored for composite application from the outset.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
GRAPHITE/PMR15 ENGINE DUCTS FAN CASES STATOR VANES COMPOSITE MATERIALS	

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